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THE INFRA-RED ABSORPTION SPECTRA OF THE HALOGEN DERIVATIVES OF METHANE

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ABSTRACT

The infra-red absorption spectra of the halogen derivatives of methane, CH_3I, CH_2Cl_2, CH_2Br_2, CH_2IBr, CH_2I_2, $CHCl_3$, $CHBr_3$, CCl_4, CBr_4, and $CBrCl_3$, were obtained between 0.8 and 3 μ by means of an infra-red spectrometer with use of a grating with 10,000 lines to the inch. A large number of new bands was discovered, owing to the greater resolution and dispersion obtained by the use of the many-lined grating. It was found that in the region of observation *no bands exist* for substances which did not have *hydrogen* in the *molecule*. For the other substances containing hydrogen there was a *similarity* of spectra. The bands do not lend themselves to an arrangement in a single series but to probably *four* series, which may be explained on the basis of four fundamental frequencies of vibration of the molecule.

A number of years ago, one of the authors noticed during some observations on the infra-red absorption of simple organic liquids what appeared to be narrow absorption bands which were incapable of resolution with a glass-prism spectrometer. Since then the technique of infra-red spectrum analysis has been improved by the use of the reflection grating introducing large dispersion and resolution and the development of a sensitive radiometer minimizing the difficulties of observation such as are experienced with the troublesome thermopile-galvanometer combination. These improvements in technique led the authors to undertake a study of the absorption spectra of the halogen derivatives of methane and ethane in liquid form at normal temperatures. The study has revealed an astonishing number of new absorption bands hitherto not disclosed by the use of apparatus of low dispersion. It is the purpose of this report to record at this time the results of the observations on the absorp-

tion of the halogen derivatives of methane between 1 and 2.5 μ inasmuch as the results are fairly complete and to report later the observations on the halogen derivatives of ethane. Attempts have been made to correlate the bands, but with moderate success only; an explanation of their origin appears at this time quite remote owing to the complexity of the systems producing the absorption.

APPARATUS AND EXPERIMENTAL PROCEDURE

The absorption spectra were obtained with a spectrometer designed in this laboratory. A beam of radiation from a Nernst glower was incident on a concave mirror and brought to focus on a slit of width 0.25 mm. Before the slit was placed a carrier for a quartz absorption cell containing the liquid to be examined. The carrier was so constructed that either the cell or a pair of quartz plates could be placed before the slit. The pair of quartz plates were used to compensate the absorption of the quartz plates of the cell, thus eliminating the absorption of the quartz from the final results.

From the slit the radiation passed on to a concave mirror of large aperture and 60-cm focal length, rendered parallel and allowed to fall on the grating of 5×5 cm aperture and ruled with 10,000 lines per inch. The dispersed radiation was returned to the mirror and brought to focus on the 0.25-mm wide vane of a sensitive radiometer, such as described by Otto Sandvik.[1] The grating was mounted on a spectrometer table previously described,[2] which allowed of rapid setting and reading.

The spectrometer ensemble was carefully calibrated by observing the spectrometer settings for the central image of the slit and the first five orders of the sodium line 5890 A. These settings could be made with an accuracy of about 0.1 of division of the spectrometer, table scale, each division corresponding to about 4 A.

The radiometer sensitivity was such that deflections as great as 350 mm with a scale at a distance of 2 m from the radiometer were obtained through the compensating plates of the quartz cell. Deflections in the range of observations were not lower than 50 mm through the plates. The stability of the radiometer system was such

[1] *Journal of the Optical Society of America*, **13**, 355, 1926.

[2] *Ibid.*, **6**, 625, 1923.

that it was free from building tremors, and there was no instability or drift of the zero due to temperature effects.

The complete range of observations was gone over with cells of different thicknesses allowing absorption through layers of liquid equal to 1.5, 7, and 14 mm. Different thicknesses of cell were necessitated by the fact that for the region between 1 and 1.6 μ the bands were faint requiring a thicker layer than in the region beyond that ranged where the absorption was more intense and the bands were not resolved with cell thicknesses greater than 1.5 mm. Some of the halogen derivatives of methane were obtained from the Eastman Kodak Company. Those not obtained from this Company were prepared for us under the direction of our colleague, F. C. Whitmore, of the Department of Chemistry. The mixed halogen derivatives, such as CH_2BrI and $CBrCl_3$, which are very rare and difficult to prepare, were prepared in particular by him.

In view of the fact that our wave-lengths do not agree with those listed by Ellis,[1] it was found advisable to set up another spectrometer with a grating having 2500 lines per inch in order to verify our results with the 10,000 line per inch grating spectrometer. Our own results are in accord, but not with those of Ellis.

RESULTS

The following halogen derivatives of methane were studied between 1 and 2.5 μ; CH_3I, CH_2Cl_2, CH_2Br_2, CH_2I_2, CH_2BrI, $CHCl_3$, $CHBr_3$, CHI_3, CCl_4 CBr_4, and $CBrCl_3$. For those substances which contain no hydrogen, no bands were found. CHI_3 exists as a solid at normal temperatures. It is slightly soluble in CCl_4, but after the solution stands for a short time, the iodine was thrown out of the CHI_3, destroying its usefulness. Faint bands were located, but inasmuch as considerable uncertainty is attached to the purity of the CHI_3, they are not listed. The results for the remainder are listed in the following tables. The second, third, and fourth columns need comment. The Roman numerals I, II, and III indicate that cells whose thicknesses were 1.5, 7, and 14 mm, respectively, were used. The figures in these columns indicate the percentage transmission at the bottom of the bands.

[1] *Physical Review*, **23**, 48, 1924; **27**, 298, 1926.

TABLE I

CH_3I Spectrometer Setting	Intensity			λ in μ	Wave Number	CH_3I Spectrometer Setting	Intensity			λ in μ	Wave Number
	I	II	III				I	II	III		
21.80	....	....	90	.8858	1128.3	41.48	30	10	....	1.6590	6027.7
27.20	....	....	89	1.1014	9079.4	42.36	55	10	....	1.6934	5905.3
27.56	....	90	78	1.1157	8963.0	42.82	38	8	....	1.7105	5846.2
28.00	....	64	34	1.1332	8824.6	43.14	f	27	....	1.7228	5804.5
28.68	....	40	15	1.1602	8619.2	44.10	82	32	....	1.7590	5685.0
33.24	....	35	25	1.3400	7462.7	45.76	....	81	....	1.8217	5489.4
33.95	....	43	15	1.3677	7311.5	46.44	....	56	....	1.8474	5413.0
34.28	....	53	29	1.3806	7243.2	47.14	....	f	....	1.8737	5337.0
34.85	....	69	54	1.4029	7128.1	47.90	....	60	....	1.8835	5309.3
35.78	....	57	40	1.4391	6948.8	48.00	....	70	....	1.9058	5247.2
36.78	....	27	10	1.4781	6765.4	48.98	....	65	60	1.9425	5148.0
37.22	....	62	50	1.4953	6687.6	52.75	....	45	....	2.0820	4803.1
41.16	62	10	....	1.6465	6073.5	54.05	....	50	....	2.1297	4695.7

TABLE II

CH_2CL_2 Spectrometer Setting				λ in μ	Wave Number	CH_2CL_2 Spectrometer Setting	Intensity			λ in μ	Wave Number
	I	II	III				I	II	III		
21.75	....	....	88	......	......	42.37	31	....	10	1.6933	5905.6
25.20	....	....	92	......	......	42.88	47	....	12	1.7128	5838.4
27.46	....	....	88	1.1119	8993.6	43.18	68	....	28	1.7244	5799.1
27.72	....	....	73	1.1221	8911.8	44.29	....	....	60	1.7662	5661.9
28.35	....	....	30	1.1472	8716.9	44.84	....	....	64	1.7872	5595.3
28.51	....	....	18	1.1535	8669.3	45.26	....	....	54	1.8030	5546.3
28.88	....	....	72	1.1681	8560.9	45.61	....	....	38	1.8162	5506.0
33.29	....	....	63	1.3419	7452.1	46.20	....	....	20	1.8384	5439.5
33.93	....	....	37	1.3669	7315.8	46.68	....	....	38	1.8564	5386.8
34.46	....	....	64	1.3876	7206.7	47.17	....	....	36	1.8748	5332.9
34.69	....	....	48	1.3975	7155.6	47.73	....	....	15	1.8959	5274.5
35.20	....	....	14	1.4166	7059.2	48.44	....	....	48	1.9253	5202.1
35.62	....	....	55	1.4330	6978.4	48.90	....	....	54	1.9393	5156.5
36.54	....	....	64	1.4688	6808.3	49.61	....	....	52	1.9658	5087.0
37.14	....	....	79	1.4921	6702.0	50.26	....	....	48	1.9898	5025.6
37.35	....	....	77	1.5002	6665.8	51.00	....	....	70	2.0178	4955.9
38.58	....	....	88	1.5477	6461.2	51.64	....	....	64	2.0412	4899.1
38.84	....	....	85	1.5578	6419.3	52.38	....	....	47	2.0683	4834.9
41.23	42	....	10	1.6488	6065.0	53.20	....	....	....	......	......
42.24	32	....	10	1.6883	5923.1	54.70	....	....	....	......	......

TABLE III

CH_2Br_2 Spectrometer Setting	Intensity I	Intensity II	Intensity III	λ in μ	Wave Number	CH_2Br_2 Spectrometer Setting	Intensity I	Intensity II	Intensity III	λ in μ	Wave Number
21.74	....	....	90	.8835	11318.	43.31	25	15	14	1.7290	5785.4
25.29	....	....	89	1.0257	9749.5	43.67	....	58	38	1.7427	5738.2
27.38	....	....	86	1.1087	9019.6	44.79	90	88	81	1.7852	5601.6
27.72	....	....	57	1.1222	8852.7	45.17	93	73	52	1.7995	5556.9
28.42	....	....	18	1.1499	8696.4	45.54	95	83	68	1.8142	5512.1
28.66	....	....	46	1.1595	8624.4	46.00	....	88	76	1.8309	5461.8
33.38	....	....	62	1.3455	7432.2	46.92	68	70	50	1.8655	5360.5
34.06	....	....	26	1.3720	7288.6	47.33	....	40	25	1.8807	5317.2
34.20	....	....	38	1.3775	7259.5	48.00	....	65	45	1.9055	5248.2
35.14	....	....	54	1.4142	7071.1	48.17	....	61	42	1.9125	5228.8
35.48	....	....	10	1.4275	7005.3	48.80	....	53	35	1.9357	5166.1
36.16	....	....	66	1.4540	6877.6	49.94	....	65	48	1.9780	5055.6
36.97	....	....	57	1.4855	6731.7	50.45	....	80	65	1.9967	5008.5
37.24	....	....	73	1.4960	6684.5	51.10	....	82	70	2.0215	4949.0
37.94	....	....	84	1.5230	6566.0	51.88	....	67	50	2.0495	4879.3
38.20	....	....	82	1.5330	6523.1	54.30	....	58	43	2.1386	4675.6
40.00	....	....	82	1.6025	6240.3	55.20	....	66	50	2.1715	4605.1
41.07	27	14	12	1.6430	6086.4	57.25	....	50	38	2.2454	4557.3
42.19	17	11	11	1.6865	5929.4	58.80	....	32	13	2.3008	4346.4
42.30	18	12	11	1.6906	5915.0						

TABLE IV

CH_2I_2 Spectrometer Setting	Intensity I	Intensity II	Intensity III	λ in μ	Wave Number	CH_2I_2 Spectrometer Setting	Intensity I	Intensity II	Intensity III	λ in μ	Wave Number
21.83	....	....	84	.8871	11273.0	44.00	70	....	10	1.7551	5697.7
25.56	....	....	90	1.0364	9648.8	44.50	....	....	50	1.7741	5636.6
27.52	....	....	92	1.1142	8975.8	45.62	....	....	78	1.8165	5505.1
27.89	....	....	58	1.1290	8857.4	46.43	....	....	32	1.8470	5414.2
28.58	....	....	12	1.1562	8649.0	46.96	....	....	68	1.8669	5356.5
29.00	....	....	80	1.1728	8526.6	47.20	....	....	66	1.8761	5330.2
33.67	....	....	68	1.3567	7370.8	48.00	....	....	57	1.9080	5246.6
34.38	....	....	40	1.3845	7222.8	48.16	....	....	50	1.9120	5230.1
34.80	....	....	55	1.4009	7138.1	48.96	....	....	15	1.9417	5150.1
35.30	....	....	85	1.4204	7040.2	49.74	....	....	36	1.9705	5074.9
35.98	....	....	8	1.4470	6910.9	49.86	....	....	36	1.9751	5063.1
36.84	....	....	70	1.4805	6903.7	50.55	....	....	34	2.0040	4990.0
37.71	....	....	64	1.5142	6754.5	52.16	....	....	32	2.0605	4853.2
38.00	....	....	80	1.5253	6556.1	53.22	....	....	70	2.0991	4763.9
39.10	....	....	85	1.5679	6378.0	54.07	....	....	40	2.1302	4694.4
41.30	32	....	....	1.6520	6053.3	55.00	....	....	72	2.1643	4620.4
42.41	24	....	....	1.6949	5900.0	55.50	....	....	71	2.1822	4582.1
42.75	20	....	....	1.7079	5855.1	56.04	....	....	62	2.2020	4541.4
43.34	92	....	....	1.7300	5780.4	59.20	....	....	20	2.3132	4319.2

TABLE V

CH_2IBr Spectrometer Reading	Intensity			λ in μ	Wave Number	CH_2IBr Spectrometer Reading	Intensity			λ in μ	Wave Number
	I	II	III				I	II	III		
21.80			68			42.57	22	12		1.7010	5878.8
25.40			82			43.60	65	18		1.7400	5747.1
27.44			88	1.1111	9007.4	44.00		64		1.7552	5697.4
27.79		80	62	1.1249	8869.2	44.63		87		1.7790	5621.1
28.51		40	14	1.1535	8669.3	44.90		88		1.7893	5588.7
28.82		83	65	1.1657	8578.5	45.28		88		1.8038	5543.8
33.51		83	70	1.3505	7404.7	45.76		65		1.8217	5489.4
33.79		95	93	1.3615	7344.8	46.60		84		1.8534	5395.5
34.18		61	38	1.3767	7262.9	48.10		28		1.9096	5236.7
34.48		77	54	1.3887	7201.0	49.61		60		1.9659	5086.7
35.68		30	10	1.4353	6967.2	51.08		70		2.0207	4948.7
36.50		84	73	1.4677	6813.4	51.32		80		2.0295	4927.3
37.34		81	69	1.4998	6667.5	52.10		80		2.0583	4858.4
37.55		86	76	1.5080	6642.3	52.80		65		2.0839	4798.7
41.18	34	12		1.6473	6070.5	55.85		45		2.1932	4559.5
42.28	22	12		1.6898	5917.9						

TABLE VI

$CHCl_3$ Spectrometer Setting	Intensity			λ in μ	Wave Number	$CHCl_3$ Spectrometer Setting	Intensity			λ in μ	Wave Number
	I	II	III				I	II	III		
25.10			90	1.0180	9823.2	41.50			52	1.6597	6025.2
28.50			24	1.1530	8673.1	42.32	28	18	4	1.6915	5911.9
29.88			94	1.2077	8280.3	43.44		94	78	1.7340	5767.0
30.12			88	1.2173	8214.9	45.75			72	1.8213	5490.5
33.52			95	1.3509	7400.2	46.40		57	37	1.8459	5417.4
33.75			92	1.3598	7354.0	46.80		32	22	1.8610	5373.8
33.85			91	1.3637	7333.0	47.72		82	62	1.8955	5275.6
34.05			91	1.3716	7290.8	50.75			72	2.0087	4978.3
34.28			78	1.3807	7242.7	51.88			58	2.0501	4877.8
35.05			8	1.4107	7088.7	53.04			70	2.0925	4779.0
36.60			94	1.4710	6798.1	53.50			65	2.1094	4740.7
37.10			91	1.4905	6709.1	55.70			85	2.1895	4567.3
37.40			84	1.5020	6657.8	56.90			73	2.2330	4478.3
38.18			79	1.5322	6526.6	58.00			55	2.2724	4400.6
39.90			94	1.5985	6255.9	58.90			25	2.3043	4339.7
40.60			94	1.6252	6153.1	60.50			45	2.3617	4234.2
41.08			88	1.6434	6084.9						

TABLE VII

$CHBr_3$ Spectrometer Setting	Intensity I	Intensity II	Intensity III	λ in μ	Wave Number	$CHBr_3$ Spectrometer Setting	Intensity I	Intensity II	Intensity III	λ in μ	Wave Number
21.80	....	....	91	......	......	43.38	....	....	55	1.7316	5775.0
25.26	....	....	84	1.0245	9760.9	47.70	....	54	28	1.8948	5277.6
28.50	....	....	21	1.1530	8673.0	48.06	....	38	23	1.9082	5240.4
30.50	....	....	93	1.2322	8115.5	52.80	....	....	82	2.0839	4798.7
35.42	....	....	10	1.4253	7016.1	54.25	....	....	74	2.1367	4680.1
36.20	....	....	89	1.4556	6870.0	56.70	....	....	68	2.2258	4492.8
37.98	....	....	88	1.5245	6559.5	57.10	....	....	78	2.2402	4463.9
38.70	....	....	83	1.5523	6442.0	57.25	....	....	77	2.2455	4453.4
39.38	....	....	80	1.5786	6334.3	59.10	....	....	48	2.3116	4326.0
40.76	....	....	94	1.6316	6128.9	62.00	....	....	50	2.4143	4142.0
42.34	....	19	11	1.6922	5909.5						

The graph contains absorption spectra for the various substances between 1 and 2 μ. A few bands outside of those wave-lengths are listed in the tables. The Roman numerals on the graphs indicate the cell used. A glance at the graph shows generally no bands between spectrometer settings, 28.00 and 33.00. There was evidence that bands exist in this region but were very faint. They were rather wide and very shallow, and could not be located accurately by varying the thickness of the absorbing layer. A comparison with the results of Coblentz,[1] Ellis,[2] and Smith and Bord[3] reveal the fact that most of the bands listed are new.

DISCUSSION

The reason for choosing the particular sequence of compounds used after the large number of bands was discovered in one of the compounds was threefold: to learn what effect the hydrogen in the molecule had on the absorption; what effect symmetry in the molecule produced, for example, in the cases of CCl_4 and CCl_3Br; and what effect on the absorption an interchange of the halogens produced. A knowledge of these might probably lead to an analysis of the spectra.

The effect of hydrogen is obvious, for when no hydrogen is

[1] *Investigations of Infra-Red Spectra*, Vol. I, "Publications of the Carnegie Institution," No. 35, 1905.

[2] *Loc. cit.*

[3] *Journal of the American Chemical Society*, **48**, 1514, 1926.

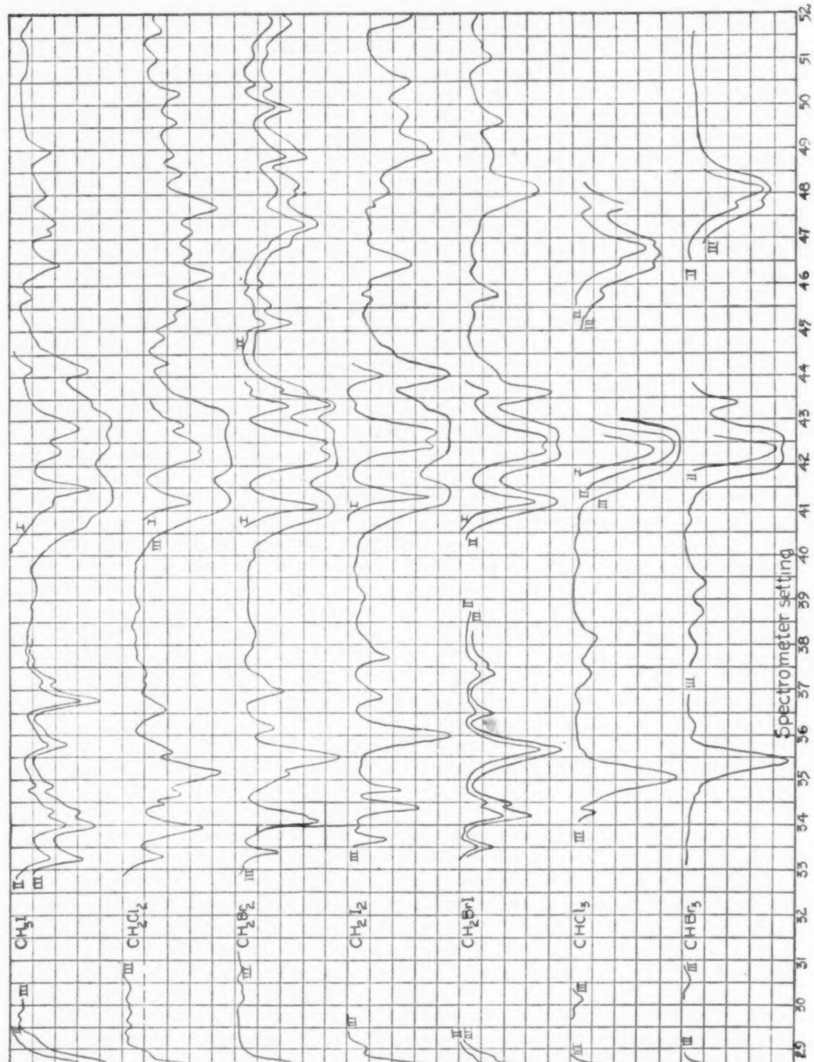

FIG. 1.—Absorption Spectra of the Halogen Derivatives of Methane

present in the molecule, no bands were found. Apparently lack of symmetry is not effective in producing the bands because the mixed halogen CCl_3Br shows no bands. Incidentally, ICl and $BrCN$ were investigated and no bands were found. It may be concluded that the bands are due to the so-called linkage C-H and could be arranged in a harmonic series. Ellis (*loc. cit.*) concluded from his work that the bands could be arranged in such a series. He investigated a series of compounds with the C-H linkage present and found a similarity of spectra. He averaged the values of the positions of similar bands, and for the group of substances he investigated, found these values fitted an expression of the form of $v_n = nv_0(1 - nx)$ due to Kratzer[1] where v_0 and x are constants and $n = 1, 2, 3. \ldots$

We, on the other hand, have attempted to fit the bands of a given substance in the Kratzer expression, for example, the fifty bands of $CHCl_3$ from our work and that of Coblentz (*loc. cit.*), and do not find that these bands fit a single equation. We have taken the bands used by Ellis and our wave-lengths and attempted to fit them to the equation, but the results do not justify conclusions.

If, on the other hand, we postulate, instead of one fundamental frequency, four fundamental frequencies, we can, along with the combination principle, arrange the fifty bands of CH_3I in series. More experimental work on the longer wave-lengths is necessary to justify the existence of the fundamentals. There appears to be justification for the assumption of a number of fundamental frequencies from the work of Dennison[2] on the methane molecule who, from theoretical considerations, found four fundamental frequencies which on computation agreed with the existing data for methane.

The effect of the halogen substitutions is interesting. Certain important bands shift very slightly to a lower frequency when a halogen of greater atomic number replaces the chlorine atom or atoms. In the subjoined table the columns I and II give the wave numbers of some strong bands that shift scarcely at all. Column III contains the wave numbers of some prominent bands that shift considerably, and column IV is obtained by subtracting column III from column IV.

[1] *Zeitschrift für Physik*, **3**, 289, 1920.

[2] *Astrophysical Journal*, **62**, 84, 1925.

It appears that the interval between the shifting bands as indicated in column III and the bands in column IV increases with the weights of the halogens present. Column I indicates that the weights

	I	II	III	IV
CH_3I	8619	5846	....	....
CH_2I_2	8649	5855	6911	1056
CH_2BrI	8669	5879	6967	1088
CH_2Br_2	8696	5915	7005	1090
CH_2Cl_2	8669	5905	7059	1154
CHI_3	....	5890	6940	1050
$CHBr_3$	8673	5909	7016	1107
$CHCl_3$	8673	5912	7089	1177

of the halogens present have very little influence on the position of these bands. The mixed compound CH_2BrI shows bands intermediate between the corresponding bands of CH_2Br_2 and CH_2I_2. If the *Br* and *I* atoms acted independently, one might expect a double band in the neighborhood of wave number 6967, or possibly a broad band. It thus appears that this band is due to the ensemble of halogen atoms in the molecule.

It is significant that the absence of hydrogen in the molecule leads to no bands in the region between 0.8 and 3 μ.

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EVIDENCE FOR THE GRAVITATIONAL DISPLACEMENT OF LINES IN THE SOLAR SPECTRUM PREDICTED BY EINSTEIN'S THEORY[1]

By CHARLES E. ST. JOHN

ABSTRACT

Material.—The observational data are the *wave-lengths of 1537 spectral lines at the center and of 133 at the edge of the sun*, and their wave-lengths in a vacuum source.

Precision of the measures.—The probable error of single solar lines is ±0.0008 A. For groups of 40 lines, as in Table VII, the probable deviation from the mean is ±0.0003 A, and for groups of 33 lines, as in Table IX, ±0.0004 A. These uncertainties are small in comparison with the displacements predicted by the theory of relativity, which average 0.0100 A.

Other causes of line-displacement.—The discussion is preceded by consideration of *conditions* in solar and stellar atmospheres *that produce displacements* of lines. In stellar atmospheres radial velocity of recession determined by high-level lines is greater, and by low-level lines less, than that of lines of medium level. The displacements to the red at the center of the sun are greater for high-level, and less for low-level, lines than for lines of medium level of the same spectral region, by amounts consistent with the position of the sun in the evolutionary sequence (Fig. 1). These extra-Einsteinian phenomena require that, if lines at any level give the predicted displacement, lines of higher level give more, and lines of lower level less, than the predicted amount.

At the center of the sun.—Each of the 586 iron lines shows a displacement to the red, for sun *minus* vacuum, whose average is ±0.0083 A. The mean displacement for lines of medium level (520 km) is ±0.009 A; the theoretical Einsteinian displacement is +0.0091 A (Table X). For lines of higher level of class *b* (840 km) it is 0.0027 A greater, and for low-level lines (350 km) it is 0.0026 A less, than the calculated displacement (Table VII).

The general results for iron are confirmed by 6 lines of silicon, 18 lines of manganese, 402 lines of titanium, and 515 lines of cyanogen.

At the edge of the sun.—Lines of iron to the number of 133 give at the limb a mean red displacement for high- and low-level lines which is 0.0015±0.0004 A greater than that calculated from the theory of general relativity. This small residual, if real, is a true limb-effect. By themselves the lines of very low level give the predicted displacement. The progression shown in the fifth column of Table VII disappears. From all *CN* lines in the 3883 band the mean displacement at the edge of the sun is +0.0072 A. From 184 lines better suited to measurement, it is +0.0076 A. The calculated displacement is +0.0081 A.

Interpretation.—Lines in widely different spectral regions but at the same low level give negative values for O−C that are proportional to wave-length and hence are attributable to upward currents near the photosphere (Table XI). This interpretation is confirmed by the increase in wave-length at the limb and by the vanishing of the negative residuals for very low-level lines which there, in the absence of line-of-sight velocities, give the predicted displacement (Table IX).

In the higher regions of the sun's atmosphere displacements to the red may be brought about, according to Milne and Merfield, through the greater number of atoms absorbing from the red edge of the line—many of the upward-moving atoms normally absorbing from the violet edge having escaped owing to the high velocities engendered by the successive absorption and emission. The effect should increase with height. This is confirmed by the lines of exceptionally high level (Table V).

Level the determinative condition.—According to atomic theory, lines of lowest excitation potential are due to electronic transitions of greatest probability and repre-

[1] *Contributions from the Mount Wilson Observatory, Carnegie Institution of Washington*, No. 348.

sent the highest level for the vapor of a given element. Such lines will be the strongest and of highest level. Lines of different elements of very different intensities, but at the same level, give equal red displacements; while for lines of the same solar intensity, but at widely different levels, the lines of higher level give the greater red displacements. This points to level of origin rather than line-intensity as the controlling factor in line-displacement (Table III).

Relative levels of origin.—Any one of five methods may be used in allocating the levels, since all agree as to the order of levels: (1) solar rotation; (2) the Evershed effect; (3) flash spectra; (4) excitation potential; (5) deviations from relativity predictions.

Conclusion.—The investigation confirms by its greater wealth of material and in greater detail the announcement made at the Symposium on Eclipses and Relativity in Los Angeles, 1923, that the causes of the differences at the center of the sun between solar and terrestrial wave-lengths are the slowing of the atomic clock in the sun according to Einstein's theory of general relativity and conditions equivalent to radial velocities of moderate cosmic magnitude and in probable directions, whose effects vanish at the edge of the sun.

SOLAR PHENOMENA CONCERNED IN THE PROBLEM OF RELATIVITY

Any interpretation of the observed differences between wave-lengths in the sun's atmosphere and the corresponding wave-lengths as measured in terrestrial laboratories must take into account conditions and phenomena known to occur in stellar atmospheres. In order to put the general reader in touch with the essential features of the problem, the necessary facts, together with certain general considerations, will be summarized and discussed under the following headings: (*a*) "Magnitude of the Relativity Displacement," (*b*) "Precision of Measurement of Lines in the Solar Spectrum," (*c*) "Pressure in the Solar Atmosphere," (*d*) "Levels Defined by Fraunhofer Lines," (*e*) "Radial Currents in Solar and Stellar Atmospheres or Their Equivalent." These points will be taken up in detail before proceeding to the observations and the related discussion.

a) MAGNITUDE OF THE RELATIVITY DISPLACEMENT

The theoretical value of the gravitational displacement is proportional to M/R (M = mass, R = radius). It also varies directly as the wave-length. For the solar spectral lines it is equal to the Fizeau-Doppler effect corresponding to a velocity of 0.635 km/sec. away from the observer. In angstrom units, the theoretical displacements to the red for the sun, in the spectral regions included in these observations, are:

Wave-lengths.....	3800	4250	4725	5675	6600 A
Displacements....	+0.008	+0.009	+0.010	+0.012	+0.014

For Sirius and Procyon it is of the same order as for the sun, while for Arcturus it is a small fraction of that value,[1] and, in any case, far too small for measurement on ordinary stellar spectrograms except for such a remarkable star as the companion of Sirius, for which Adams[2] found a gravitational shift of 21 km/sec., agreeing, within the errors of observation, with the amount predicted by Eddington.[3]

b) PRECISION OF MEASUREMENT OF LINES IN THE SOLAR SPECTRUM

To determine the agreement attainable by different observers, using different apparatus, the Mount Wilson Observatory arranged a few years ago with Mr. Evershed, then at Kodaikanal, India, for the independent measurement of the wave-lengths of the fourteen solar lines listed in Table I.

The measures show practical agreement in the mean, with an average difference of only ± 0.0015 A; nevertheless, two lines, λ 4447 and λ 4494, illustrate the care necessary in such measures to reduce the effect of insidious errors to a minimum. The mean sun *minus* arc for the group is $+0.005$ A, while these lines give

	Mount Wilson Sun−Arc	Kodaikanal Sun−Arc
λ 4447	$+0.007$ A	$+0.012$ A
λ 4494	$+0.003$	0.000

For both lines the measures at the two observatories deviate from the mean in the same direction, above for λ 4447 and below for λ 4494. The lines are of intensity 6 in the solar spectrum, but λ 4447 has a line of 00 intensity 0.06 A to the red, and λ 4494 a line of 00 intensity 0.08 A to the violet. The separation is so small that the strong and weak lines are in contact or even partially overlap, so that the influence upon the measured wave-lengths depends upon the intensity of the spectrograms. Rowland's table gives 14,000 lines in the region under consideration. The spectra of elements known to be present in the sun's atmosphere include a far larger number of lines, many of which might reasonably be expected to

[1] For data on stellar masses and diameters, see Table IV.

[2] *Mt. Wilson Communications*, No. 94; *Proceedings of the National Academy of Sciences*, 11, 382, 1925.

[3] *Monthly Notices, R.A.S.*, 84, 308, 1924.

occur. The measured position of any moderately strong line may be slightly affected by a nearly coincident, but not observable, weak line. The effect of random errors thus introduced may be eliminated by using a very large number of lines, as in the present investigation, which depends on more than 1500 apparently free-standing lines.

Further evidence of the dependence that may be placed upon the measures is given by comparing the wave-lengths as measured at Mount Wilson Observatory with the A.O.B.S. wave-lengths[1] for

TABLE I

ORDER OF AGREEMENT BETWEEN MEASURES

Mount Wilson	Kodaikanal	Mount Wilson *minus* Kodaikanal	Mount Wilson	Kodaikanal	Mount Wilson *minus* Kodaikanal
4337.057	.055	+0.002 A	4454.390	.391	−0.001 A
4375.946	.946	.000	4461.662	.662	.000
4388.416	.413	+ .003	4466.564	.565	− .001
4427.319	.318	+ .001	4469.385	.384	+ .001
4442.351	.352	− .001	4484.229	.231	− .002
4443.203	.201	+ .002	4489.750	.751	− .001
4447.730	.735	−0.005	4494.575	.572	+0.003

Sum, positive residuals, Mt. Wilson−Kodaikanal .... +0.012
Sum, negative residuals, Mt. Wilson−Kodaikanal .... −0.011

the 201 lines common to the two lists. The Mount Wilson wave-lengths are based upon the secondary standards adopted by the International Astronomical Union in Rome, 1922. The A.O.B.S. wave-lengths are based upon the new neon standards which, in the region compared, differ by 0.002 A from the Rome standards. When this is taken into consideration, the result of the comparison is:

Mean systematic difference, Mt. W.−A.O.B.S. = +0.0002 A .

The mean deviation between independent measurements of even limited groups of solar lines shows an accuracy far greater than is required to establish displacements of the magnitude predicted by the theory of relativity. In this connection it may be recalled that, in the observations upon which the accepted existence and

[1] *Publications of the Allegheny Observatory*, **6**, 105 (No. 7), 1926.

magnitude of the general magnetic field of the sun rest, the maximum differential displacement in latitude 45° is 0.001 A,[1] a tenth of the average relativity effect.

c) PRESSURE IN THE SOLAR ATMOSPHERE

Until quite recent years a pressure of 5–7 atmospheres was assumed to obtain in the region of the sun's atmosphere accessible to spectroscopic investigation. It is now the accepted conclusion among solar investigators that the maximum pressure in the reversing layer is so low that for spectroscopic purposes it may be taken as zero. The low pressure is shown by direct spectroscopic measures[2] and by deductions from the theory of ionization.[3] The gravitation of the earth produces a total pressure upon its surface equal to the weight of its atmosphere less the centrifugal effect of rotation, but in the sun and in all bodies of stellar character the pressure of radiation outward yields a counter force that tends to balance the effect of gravitation upon their enveloping atmospheres, and for the high-level portions it nearly equals the gravitational attraction. In this respect the sun is in no way peculiar, but behaves like any other star.[4]

d) LEVELS DEFINED BY FRAUNHOFER LINES

The concept that the Fraunhofer lines in the spectra of the sun and stars refer to definite levels is steadily gaining acceptance and application.[5] The observational evidence for this concept rests upon

[1] Hale, Seares, van Maanen, and Ellerman, *Mt. Wilson Contr.*, No. 148; *Astrophysical Journal*, **47**, 206, 1918.

[2] Evershed, *Kodaikanal Bulletin*, No. 18, 1909, and No. 36, 1916; Perot, *Comptes rendus*, **172**, 578, 1921; Salet, *ibid.*, **174**, 151, 1922; St. John and Babcock, *Mt. Wilson Contr.*, No. 278; *Astrophysical Journal*, **60**, 32, 1924.

[3] Saha, *Philosophical Magazine*, **40**, 809, 1920; St. John, *Contributions of the Jefferson Physical Laboratory*, **15**, 1921; Russell, *Mt. Wilson Contr.*, No. 225; *Astrophysical Journal*, **55**, 119, 1922; Stewart, *Physical Review*, **22**, 324, 1923.

[4] Eddington, *Monthly Notices, R.A.S.*, **77**, 16, 596, 1917; **83**, 32, 98, 431, 1922; *Astrophysical Journal*, **48**, 215, 1918; Fowler and Milne, *Monthly Notices, R.A.S.*, **83**, 417, 1923; St. John and Adams, *Mt. Wilson Contr.*, No. 279; *Astrophysical Journal*, **60**, 43, 1924.

[5] Rufus, Aldrich, R. H. Curtiss, *Popular Astronomy*, **32**, 22, 218, 228, 471, 547, 1924; R. H. Curtiss, *Publications of the Astronomical Society of the Pacific*, **38**, 148, 1926; Joy, *Mt. Wilson Contr.*, No. 311; *Astrophysical Journal*, **63**, 281, 1926.

the concordant results from solar rotation, flow near spots, flash spectra (Table II), differences between the spectra of limb and center, progression in excitation potentials, and the observed decrease in the strength of the general magnetic field with the heights above the photosphere at which the lines used have their origin.[1]

TABLE II

CORRELATIONS IN LEVEL

A. Data from Various Sources*

Lines	Rotation Obs.—Norm.†	Observer	Flow Near Spots	Height
	km/sec.		km/sec.	km
H_3 and K_3 *Ca+*	+0.20	St. John and Ware	1.80 in	12000
Hα hydrogen	+ .11	Adams and Evershed	1.50 in	10000
4226 *Ca*	+ .06	Adams	0.06 in	2100
High-level *Fe*	+ .02	Evershed	.00	1200
Medium-level *Fe*	.00	Adams and Evershed	.40 out	400
4196 *La+*	−0.03	Adams	0.75 out	Low

B. Simultaneous Observations at High and Low Level‡

Lines	Equatorial Velocity	Observer	Flow Near Spots	Height
	km/sec.		km/sec.	km
5172 and 5183 *Mg*	2.03	St. John and Ware	0.36 in	2250
5165 and 5225 *Fe*	1.95	St. John and Ware	0.60 out	350
H_3 and K_3 *Ca+*	2.12	St. John and Ware	1.80 in	12000
Weak *CN* lines	1.87	St. John and Ware	0.63 out	Low

* Adams, *Mt. Wilson Contr.*, No. 33; *Astrophysical Journal*, **29**, 110, 1909; and *Mt. Wilson Contr.*, No. 43; *Astrophysical Journal*, **31**, 30, 1910; Mitchell, *Astrophysical Journal*, **38**, 407, 1913; St. John, *Mt. Wilson Contr.*, Nos. 69, 74, 88; *Astrophysical Journal*, **37**, 322, 1913; **38**, 341, 1913; **40**, 356, 1914; Fox, *Astrophysical Journal*, **57**, 234, 1923; Evershed, *Monthly Notices R. A. S.*, **85**, 607, 1925.

† Norm. = Linear velocity for lines of medium level.

‡ St. John and Ware, *Annual Reports of the Mt. Wilson Observatory*, 1915, 1918.

At the high level of *Ca+* the eastward velocity in the equatorial region is 0.23 km/sec. greater than that shown by the very low-lying vapors of lanthanum. For that portion of the hydrogen atmosphere responsible for the *Hα* line the period of the sun's rotation is 24 days, while for the lower reversing layer it is 25.35 days. The relative linear velocities represent a steady east wind of approxi-

[1] Hale, Seares, van Maanen, and Ellerman, *Mt. Wilson Contr.*, No. 148; *Astrophysical Journal*, **47**, 206, 1918.

mately 400 km an hour in the upper atmosphere. In observations for solar rotation, we seem forced to the view that the specific behavior of Fraunhofer lines refers to restricted levels in the sun's atmosphere. The measures are relative and between lines of the same intensity and character. They are therefore free from the effects of any possible asymmetry.

Around spots, the vapors from below the photosphere, raised by the spot-forming vortex, flow outward along the solar surface—the Evershed effect, the outward velocity decreasing with the elevation and eventually becoming zero. The lowered temperature of the expanding gases produces the relatively dark umbra. Over the cooled region the radiation pressure which supports the chromospheric gases is reduced, and they fall[1] and form a secondary vortex in the chromosphere in which the flow is inward, the maximum velocity of inflow occurring at the highest elevation. In the observation of these velocities we have a method of sounding the solar atmosphere and of allocating the relative levels of the lines.[2]

The determination of the absolute heights reached by the gaseous layers responsible for the Fraunhofer lines has not attained high precision, but it is sufficient to assure one that the fifth column of Table II represents relative heights, although the actual heights may be only approximately known. The data in the second, fourth, and fifth columns, Table II, are most simply interpreted in terms of level, and, when so interpreted, show the same sequence of levels from high at the top to low at the bottom of the table.

From the like order in the arrangement of levels shown by solar rotation, by flow near spots, and by flash spectra, it may confidently be inferred that the heights to which the different constituents of the sun's atmosphere rise and the relative levels of origin of the Fraunhofer lines observed in these particular regions of the sun are representative of the general solar surface. This inference is reinforced by the similar relation between level and the strength of the general magnetic field for which the observations are made along the sun's meridian.

Still other observations show that certain lines originate in low-

[1] S. R. Pike, *Monthly Notices, R.A.S.*, **87**, 56, 1926.

[2] St. John, *Mt. Wilson Contr.*, No. 69; *Astrophysical Journal*, **37**, 341, 1913.

lying layers and others in successive shells of the solar atmosphere. Thus ionized atoms, such as Ti^+, give long, lancelike lines in chromospheric spectra, in strong contrast with the shorter arrow-headed lines produced by normal atoms, though in the spectrum of the sun's disk the lines may be of the same intensity. This difference of behavior in the chromosphere is direct evidence that the atmosphere of ionized titanium is more extensive than that of the normal atom. Moreover, the sharpness of the Ti^+ lines in the spectrum of the disk and the known increase of ionization with decrease of pressure point to their high-level origin in the layers of maximum ionization. Plate I*b*, a reproduction of a small section of an eclipse spectrogram taken with Campbell's moving-plate camera in Spain, 1905, illustrates the characteristic behavior of Ti and Ti^+ lines of the same solar intensity for which the red displacements are respectively +0.009 and +0.012 A.

In comparisons of the spectra of the center and the limb of the sun, Adams[1] observed that lines of the heavy elements and the broad shading of the strongly winged lines are greatly weakened and in some cases are almost obliterated in the spectra of the limb. This he interpreted as evidence of the low level of their origin, the light from the low-lying layer being scattered in the longer path at the limb or, according to the present conception, cut off by its source's being below the optical depth.

Again, in spectrograms of planetary nebulae made with a slitless spectrograph, the diameters of the monochromatic images show the distribution in level of the gaseous shells corresponding to the bright lines, greatly emphasized, however, in comparison with the levels of distribution in the sun. One needs only to imagine a shrinking to stellar proportions to have a mental picture of levels in the sun and other stars. Through the kindness of Dr. W. H. Wright, I am able to reproduce his spectrograms[2] of N.G.C. 7662, in Plate I*a*. Similar results for the sun were observed by Paddock[3] on spectrograms taken with an objective-prism telescope located just outside the edge of the shadow at the eclipse of January 24, 1925. The

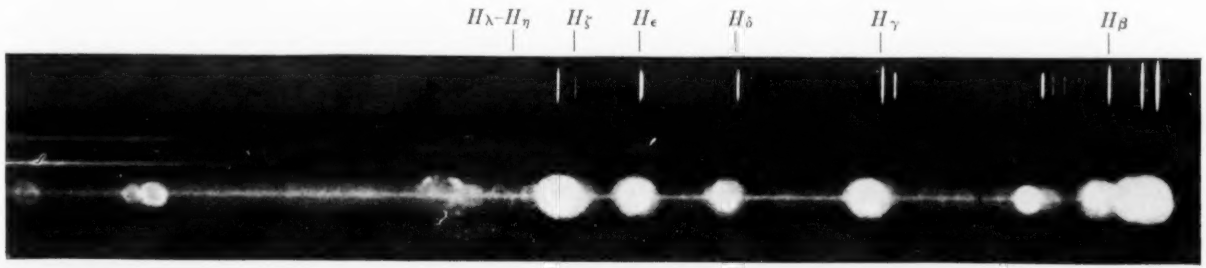
[1] *Mt. Wilson Contr.*, No. 43; *Astrophysical Journal*, **31**, 46, 1910.

[2] *Publications, Lick Observatory*, **13**, Plates XLV and XLVI, 1918.

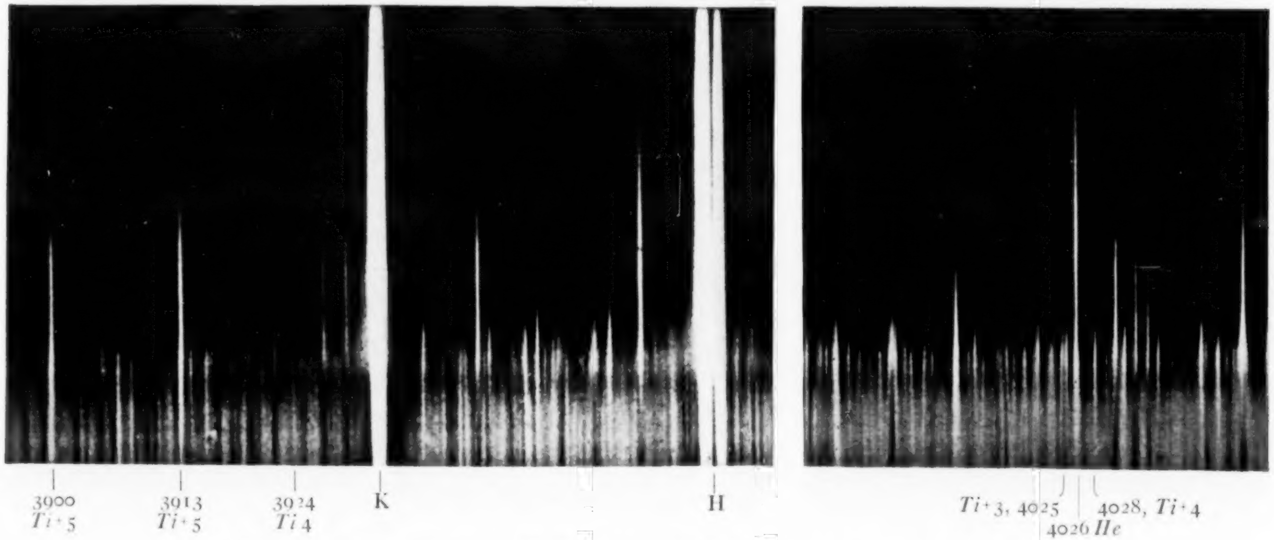
[3] *Astrophysical Journal*, **66**, 1, 1927.

PLATE I

a



b



a. Nebular Spectrograms by W. H. Wright; N.G.C. 7662 with and without Slit

b. Moving-Plate Spectrogram by W. W. Campbell; Spanish Eclipse of 1905

hydrogen arcs show positive correlation between height and intensity. The only arcs of *Ba, Fe, Sc, Sr,* and *Ti* high enough to be observed were from their ionized atoms; and the only *Cr* arcs were from atoms in the lowest energy-state.

The heights to which the constituents of the solar atmosphere rise are mainly determined by their abundance, atomic weight, ionization potential, and selective radiation-pressure; but for the same element the levels registered by the different normal lines depend upon the excitation potential and the probability of the electron transitions concerned in their production. For an element in a given state of ionization, the lines of the multiplet of lowest excitation potential and, within the multiplet, the lines on the diagonal, due to transitions of greatest probability, represent the highest elevation above the photosphere. Since atoms in this state of excitation are the most numerous, form the most abundant constituent of the substances, and contribute most to their radiation or absorption, their lines will be strong and the level high.[1]

For each element the relation between level and line-intensity should hold for lines of the same class and spectral region, but lines of a given solar intensity corresponding to different elements, or classes, or spectral regions are not necessarily at the same level.[2]

That the level of origin and not the intensity of lines is the controlling factor and determinative of the characteristic differences in displacement for lines of different solar intensity may be illustrated by comparing the sun-*minus*-vacuum displacements for lines of the same intensity but of different levels, or for lines of different intensities but of the same level, as in Table III.

For the first two pairs—lines of equal intensity—the larger displacement goes with the greater height, while for the last pair—lines of very unequal intensities but at approximately the same level—the displacements are equal. For the middle pair—ionized and normal *Ti*—the difference in level follows directly from Saha's theory,[3] according to which high ionization characterizes the lower

[1] Observational evidence on the relation of excitation potential appears in Tables VII and XIII.

[2] St. John, *Mt. Wilson Contr.*, No. 74; *Astrophysical Journal*, **38**, 343, 1913.

[3] *Philosophical Magazine*, **40**, 472 and 809, 1920.

pressure at high levels; and here again the lines of higher level show the greater displacement to the red, though the lines are of like solar intensity.

Although the classification of lines into groups for discussion is by line-intensity, it is, in accordance with the preceding discussion, fundamentally one based on level. Since the heights of individual lines are not yet exactly determined, and since, within the foregoing limitations, a close relation exists between level and intensity, relative levels, in a first approximation, may be inferred from the more accurately estimated intensities, or determined from the Evershed effect near spots, or from the differences in solar rotation.

TABLE III

RED DISPLACEMENT AND LEVEL IN THE SOLAR ATMOSPHERE

Element	No. of Lines	Mean λ	Mean Int.	Sun−Vac.	Height
					km
Ti+..........	2	3772	11.0	+0.013 A	6000
Fe...........	14	3870	11.0	.010	1100
Ti+..........	14	4250	4.7	.012	1300
Ti...........	12	4110	4.2	.009	520
Ti+..........	14	4250	4.7	.012	1300
Fe...........	12	3900	13.6	+0.012	1290

c) RADIAL CURRENTS OR THEIR EQUIVALENT

On high-dispersion spectrograms of Sirius, Procyon, and Arcturus, taken by Adams and Babcock in 1909–1910,[1] the radial velocities determined from high-level lines give positive residuals when compared with the results for lines of medium level, while lines of still lower level show negative residuals.[2] The results are shown in Table IV along with comparable data for the sun and seven other stars.

The residuals in the first line show that the line-of-sight velocity of Sirius away from the center of the solar system determined by the

[1] *Mt. Wilson Contr.*, No. 50; *Astrophysical Journal*, **33**, 64, 1911.

[2] St. John and Adams, *Mt. Wilson Contr.*, No. 279; *Astrophysical Journal*, **60**, 43, 1924.

$H\alpha$ line of high-level hydrogen is 2.6 km/sec. greater than that for lines of medium level, but that, when determined from low-level lines, it is 0.5 km/sec. smaller. Conversely, the residuals in the fourth line show that to an observer on Sirius, Procyon, Arcturus, or any other star, the motion of the sun, measured by the apparent Doppler displacement of the H_3 and K_3 lines of high-level Ca^+, would be

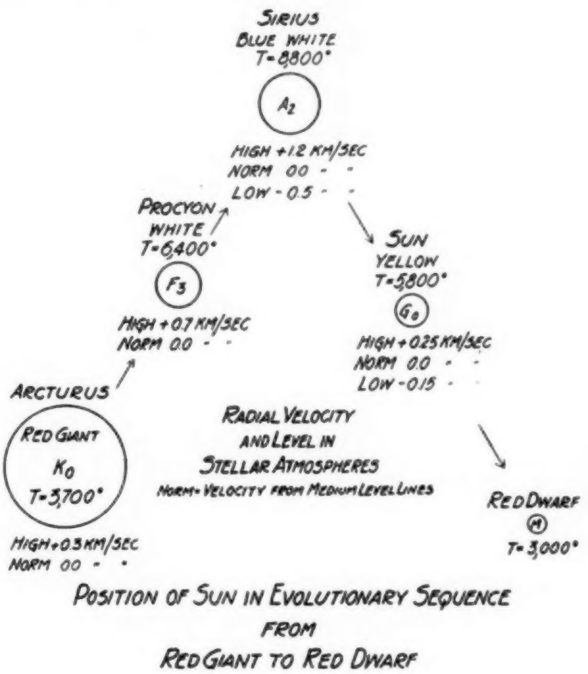


FIG. 1

0.45 km/sec. greater than that determined from lines of medium level; but, when measured by the displacement of the low-level lines of La, it would be 0.15 km/sec. smaller, and, for still lower lines, 0.25 km/sec. smaller.

On the assumption that the larger part of the material of a star is expendable in radiation, a single star might go through almost every known spectral type, starting as a massive red giant, passing through various stages to class A or B and along the main sequence perhaps as far as class M, using up its active substance on its

way.[1] When the first four stars of Table IV are arranged according to this evolutionary sequence, the magnitude of the effect seems to be correlated with temperature, being largest at the highest temperature, and, in the case of the sun, corresponding to the sun's position in the sequence (Fig. 1).

In the differential displacements of Table IV, we are concerned with phenomena that are characteristic of both solar and stellar atmospheres and independent of relativity effects. The comparison has been made by forming differences in displacement in the same spectral region; this eliminates relativity, the small change in the

TABLE IV

COMPARATIVE RADIAL VELOCITIES FOR HIGH- AND LOW-LEVEL LINES

Star	Atomic State	Sp.	Temp.	Diam	Mass	Ca^+	$H\alpha$	$H\gamma$	High	Med	Low	Very Low
Sirius........	Neutral	A2	8800°	4	2.5	......	+2.6	+2.0	+1.2	0.0	−0.5	....
Procyon......	Neutral	F3	6400	1.6	1.7	......	......	......	0.7	.0	......	....
Arcturus......	Neutral	K0	3900	3	20.0	......	......	......	.3	.0	......	....
Sun..........	Neutral	G0	5800	1	1.0	+0.43	......	......	.25	.0	−0.15	−0.25 (*Ce*+)
γ Cygni*.....	Enh.	....	......	......	......	......	......	......	......	.0	......	−1.45 (*Ce*+)
5 Giants......	Enh.	....	......	......	......	......	......	......	.40	.0	......	....
γ Cygni*.....	Enh.	....	......	......	......	......	......	......	.65	.0	......	....
δ Cephei min...	Enh.	....	......	......	......	......	......	......	.9	.0	......	....
δ Cephei max..	Enh.	....	......	......	......	......	......	......	+2.4	0.0	......	....

* Adams and Joy, *Mt. Wilson Communications*, No. 99; *Proceedings of the National Academy of Sciences*, **13**, 393, 1927.

theoretical displacement with levels arising from the change in the effective radius of the sun being quite insensible. Even for a difference in level of 10,000 km, it amounts, in the case of the sun, to only one-seventieth of the total effect.

The progressive decrease of red shift at lower levels finds a natural explanation in convection currents or their equivalent. It may fairly be assumed that convection currents are more pronounced the higher the temperature of the star; and the residuals in Table II, interpreted as Fizeau-Doppler effects, are in harmony with such a view. That Arcturus and other giants having lower temperatures than the sun show greater convection currents is not opposed to this view, since giants are of extremely low density as compared with the dwarf sun, and somewhat more rapid convection is perhaps to be expected.

[1] Russell, Dugan, and Stewart, *Astronomy*, **2**, 919, 1927.

In the case of the sun the assumption of upward currents, increasing in magnitude on nearing the photosphere, appears especially well founded and apparently justified by the behavior of easily ionized cerium (Table IV, fourth line), which gives the relatively large displacement -0.25 km/sec. The element is heavy and may be expected to occur at a very low level, an expectation confirmed by the fact that it gives a small value for the solar rotation and has a high velocity of outflow from spots. The very large negative displacement, -1.45 km/sec., that it shows in γ Cygni is also significant.

TABLE V

BEHAVIOR OF EXCEPTIONALLY HIGH-LEVEL LINES

(Unit for $\Delta\lambda$ = 0.001 A)

Line	Wave-Length		$\Delta\lambda$			Equiv. Veloc.	Evershed Effect	Height
	Sun's Center	Vac.	Obs.	Cal.	O−C	km/sec.	km/sec.	km
Ca+ (K_3)	3933.684	0.667	+17	8.5	+8.5	+0.63 dn	1.90 in	12000
Ca+ (H_3)	3968.494	.476	18	8.5	9.5	.71 dn		
Hα	6562.816	.793	23	14	9	.41 dn	1.50 in	10000
Hβ	4861.344	.327	17	10	7	.43 dn		9000
Hγ	4340.477	.466	11	9	2	.14 dn	1.00 in	6000
Mg	5183.621	.605	15	11	4	.23 dn	0.36 in	2500
Mg	5172.700	.686	14	11	3	.17 dn		
Na (D_2)	5889.977	.963	14	12	2	.10 dn	0.18 in	2300
Na (D_1)	5895.944	.930	14	12	2	.10 dn		
Ca	4226.742	0.731	+11	9	+2	+0.14 dn	0.06 in	2100

Evidence supporting the assumption of radial currents is also found in the fact that the residual displacements attributed to this source correspond to radial velocities which, for lines of the same level, are independent of wave-length. The details for a comparison of this kind appear in Table XI.

While the displacement of low-level lines to the violet in comparison with lines of medium level in the same spectral region finds a satisfactory interpretation in rising convection currents, the displacement of high-level lines to the red in a similar comparison presents an interesting question. This has been discussed by St. John and Babcock,[1] by Milne,[2] and more recently by Merfield.[3] Milne

[1] *Mt. Wilson Contr.*, No. 278; *Astrophysical Journal*, **60**, 32, 1924.

[2] *Monthly Notices, R.A.S.*, **86**, 597, 1926.

[3] Read at the Royal Society of Victoria, Melbourne, Australia, 1926.

suggests that an asymmetrical velocity-distribution among the velocities of agitation of the individual atoms would remove the difficulties he sees in the suggestion of St. John and Babcock that an asymmetry to the red may be due to a more effective absorption by a cooler downward-moving vapor. "Unfortunately," he says, "the investigation of the velocity-distribution amongst the high-level atoms given in this [his] paper shows it to be a symmetrical Maxwellian one." He suggests, however, that the clue to the explanation of the displacement to the red may be in the expulsion of outward-moving atoms under radiation pressure with a consequent excess of absorbing centers on the red edge of the lines, though the dynamical evidence is wanting. Merfield finds on his eclipse plates a widening of the H and K lines above 8000 km, and reasons along the lines of Milne's suggestion as follows:

The widening of the H and K lines above 8000 km is attributed to high ionic agitation. After emission, some of the atoms may possess large outward velocities, and the next absorption will be from the violet side of the line where the radiation is stronger than at the center of the line. Successive emissions and absorptions will endow these atoms with an increasing outward acceleration, and some may escape from the sun. The velocities of descent are hardly likely to exceed the velocities of thermal agitation. Atoms with such velocities will be retained in the sun, whereas the velocities of ascent may reach the velocity of escape. There are then more atoms absorbing from the red wing than from the violet. Hence the absorption line will appear displaced to the red, and this feature should become more prominent with increasing height. This conclusion is supported by the data in Table V.

Although the measures on such strong lines, intensity 20 and above, are not of the high precision attained for lines of intensity 2–4, they suffice to show that, as a rule, for this class of line, the higher the level, the greater the downward velocity deduced from the positive residuals.

It should be repeated that the displacements discussed in this section are differences at the center of the solar disk between lines of different levels, in the same spectral region, and hence inde-

pendent of relativity. The progression in the differences is plausibly explained as the consequence of ascending and the equivalent of descending currents, but whatever the ultimate explanation of these characteristic differences for lines of high and low level, it follows as surely as night follows day that, if the lines of any level give the predicted gravitational displacement, lines of higher level will show an excess, and lines of lower level a deficit, the deficit increasing with lowness of level, and this, it will be seen, is precisely what the observations indicate.

OBSERVATIONS OF IRON LINES AT THE CENTER OF THE SUN

The major weight of the conclusions deduced from the present investigation rests upon 497 iron lines of groups *a* and *b*, lines measurable in the arc with very high accuracy.[1] The results for these lines are confirmed by the somewhat less reliable data for 89 relatively unstable iron lines of groups *c*5, *d*5—lines showing marked pole effect in the arc[2]—for 18 similar manganese lines,[3] and for 515 closely spaced lines in the 3883 band of cyanogen. The results for the stable iron lines are further consistently supported by the data for 6 lines of silicon, 10 exceptionally high-level lines of calcium, sodium, manganese, and hydrogen, and for 402 lines of titanium measured in the vacuum arc by Brown and by Crew,[4] a total of 1537 lines.

The comparisons between the sun and arc are between the wave-lengths of the lines in the sun and the wave-lengths for the source in vacuum. In the case of iron lines of groups *a* and *b* not measured in the vacuum arc, the wave-lengths in air were reduced to the source in vacuum by applying the means of the closely agreeing pressure coefficients per atmosphere found by Gale and Adams[5] and by Babcock (unpublished). For groups *c*5 and *d*5 the coefficients are

[1] *Transactions of the International Astronomical Union* (Rome, 1922), Commission (12) des étalons de longeur d'onde.

[2] St. John and Babcock, *Mt. Wilson Contr.*, No. 106; *Astrophysical Journal*, **42**, 231, 1915.

[3] Monk, *Astrophysical Journal*, **57**, 222, 1923.

[4] *Ibid.*, **56**, 53, 1922, and **60**, 108, 1924.

[5] *Mt. Wilson Contr.*, No. 58; *Astrophysical Journal*, **35**, 10, 1912.

derived from Brown's[1] measures and Babcock's unpublished data. For manganese the laboratory data are from Monk's paper.[2]

The solar wave-lengths from λ 4000 to the red are the means of the closely agreeing grating measures of St. John and the interferometer measures of Babcock, corrected for the rotation and orbital motion of the earth. To the violet of λ 4000, they are grating measures only, based upon simultaneous exposures to the sun and arc, extending over a series of years, made with the 30-foot spectrograph and the 60-foot tower telescope in the earlier period, and with the 75-foot spectrograph and the 150-foot tower telescope in the later period. The interferometer measures were in greater part made with the Snow telescope. Plates II and III show the heads of the spectrographs and the arrangement of the accessory apparatus. Plates IV and V are reproductions of grating and interferometer spectrograms similar to those upon which the wave-length measures depend.

The results of the measures on iron lines are given in detail in Table VI under sections A, B, and C, which correspond to the following pressure classes: *b*—Lines symmetrical under pressure; energy-level medium; pressure displacement small to medium; an inclusive and complex class. *a*—Low-temperature lines, flame lines; sharp and symmetrical; energy-level low; pressure displacement small. *c*5, *d*5—High-temperature lines; asymmetrical toward the red; pole-effect large; energy-level high; pressure displacement large.

The solar and vacuum wave-lengths are given in the first and second columns, respectively. In the third column are the red displacements, sun *minus* vacuum, and in the fourth column, the differences between these displacements to the red and those calculated from general relativity. The excitation potentials of lines identified in multiplets are in the fifth column, the approximate heights[3] in the sixth, and the temperature class (King) in the seventh column.

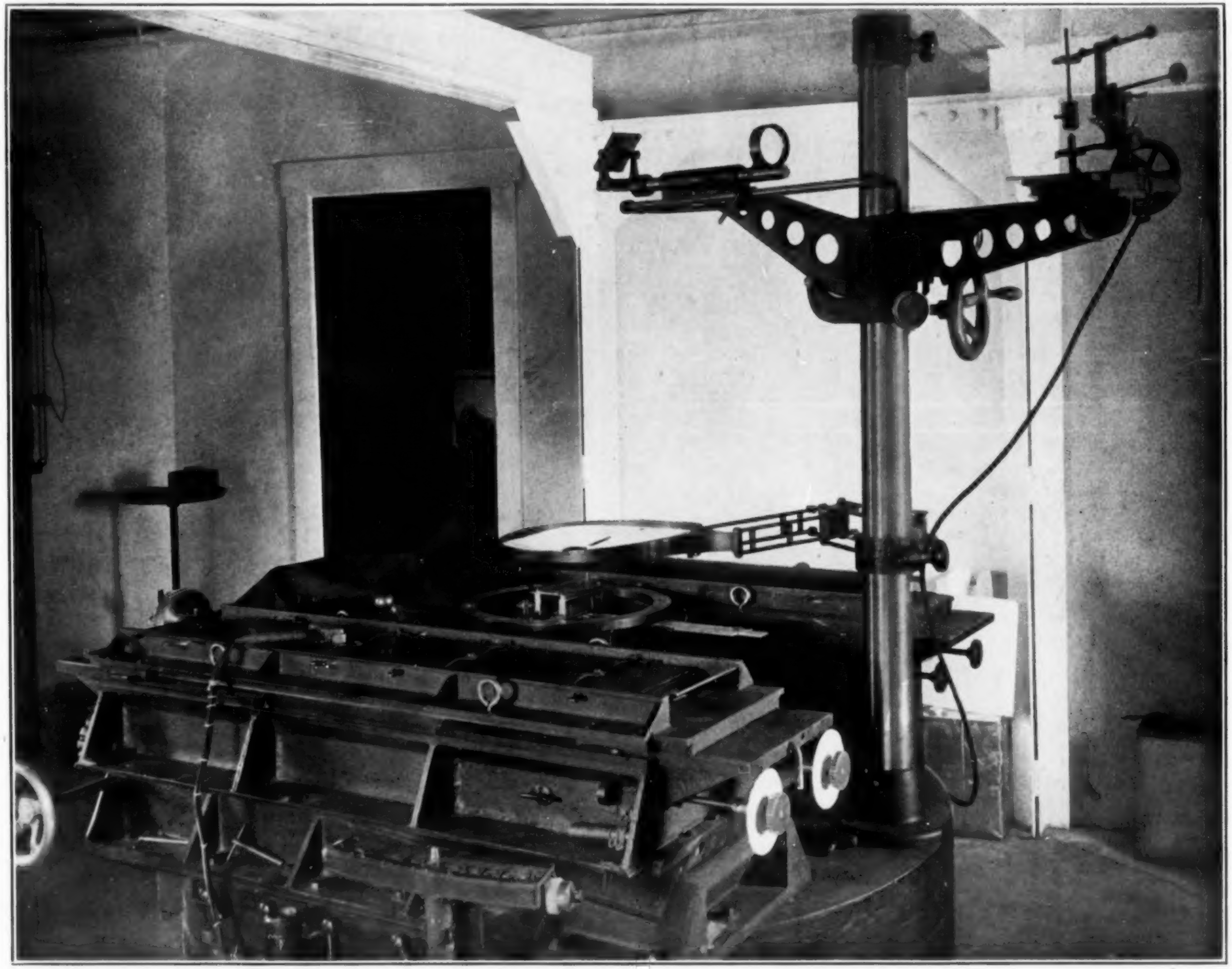
The results are summarized in Table VII. This table includes in the eighth and ninth columns additional data bearing on the levels at which the lines originate.

[1] *Astrophysical Journal*, **56**, 53, 1922.

[2] *Ibid.*, **57**, 222, 1923.

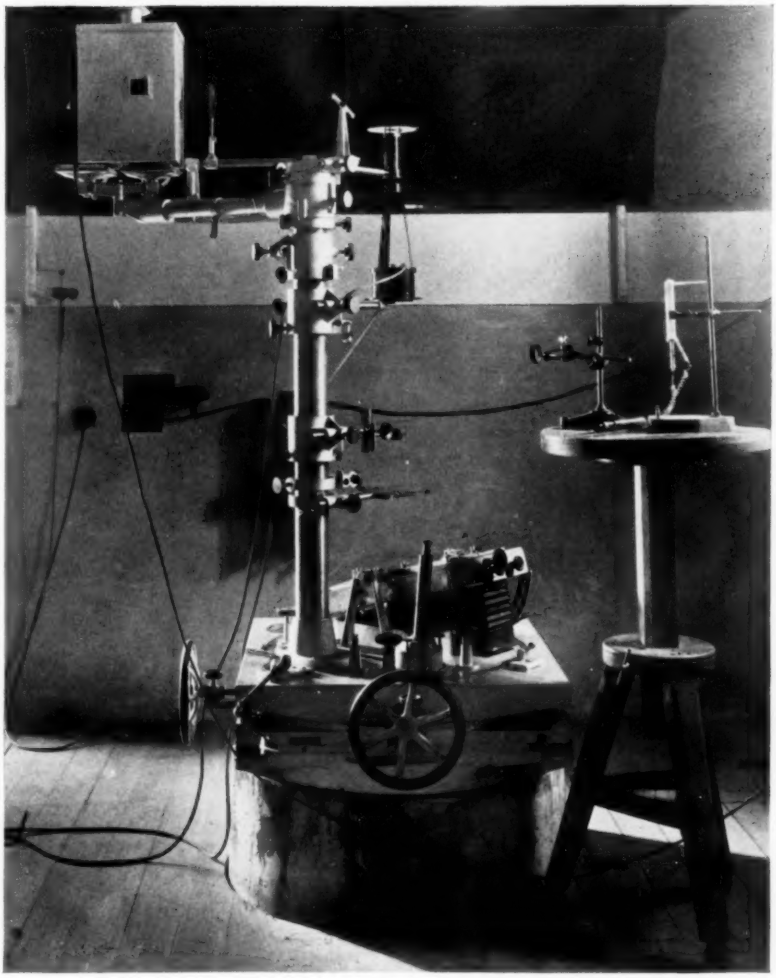
[3] Mitchell, *ibid.*, **38**, 407, 1913.

PLATE II



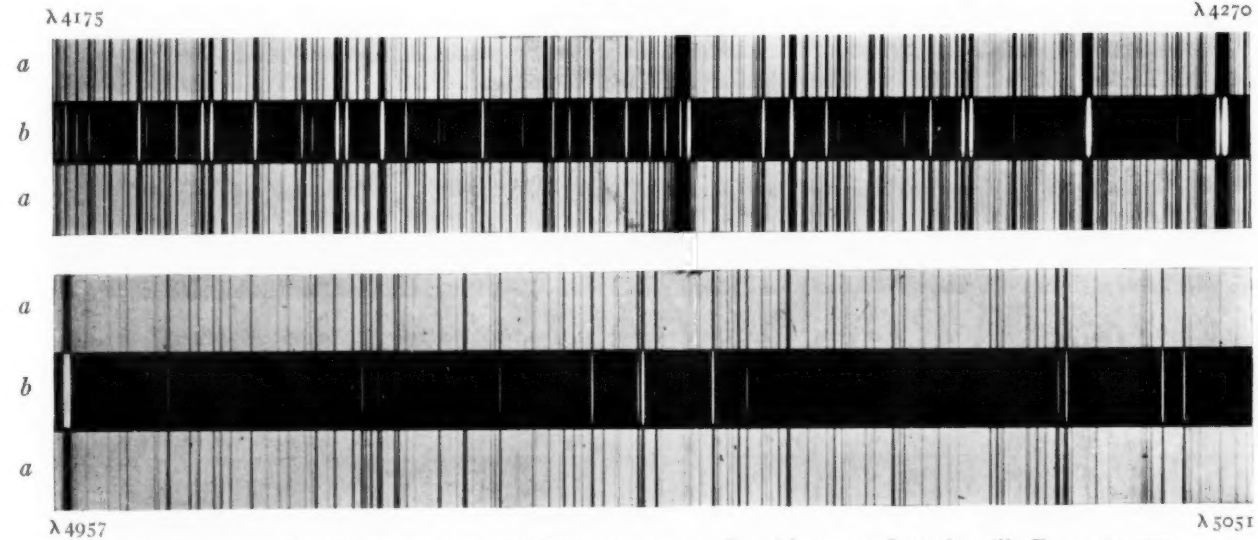
Head of 75-foot Spectrograph of 150-foot Tower Telescope, Showing Mounting for Comparison Arc

PLATE III



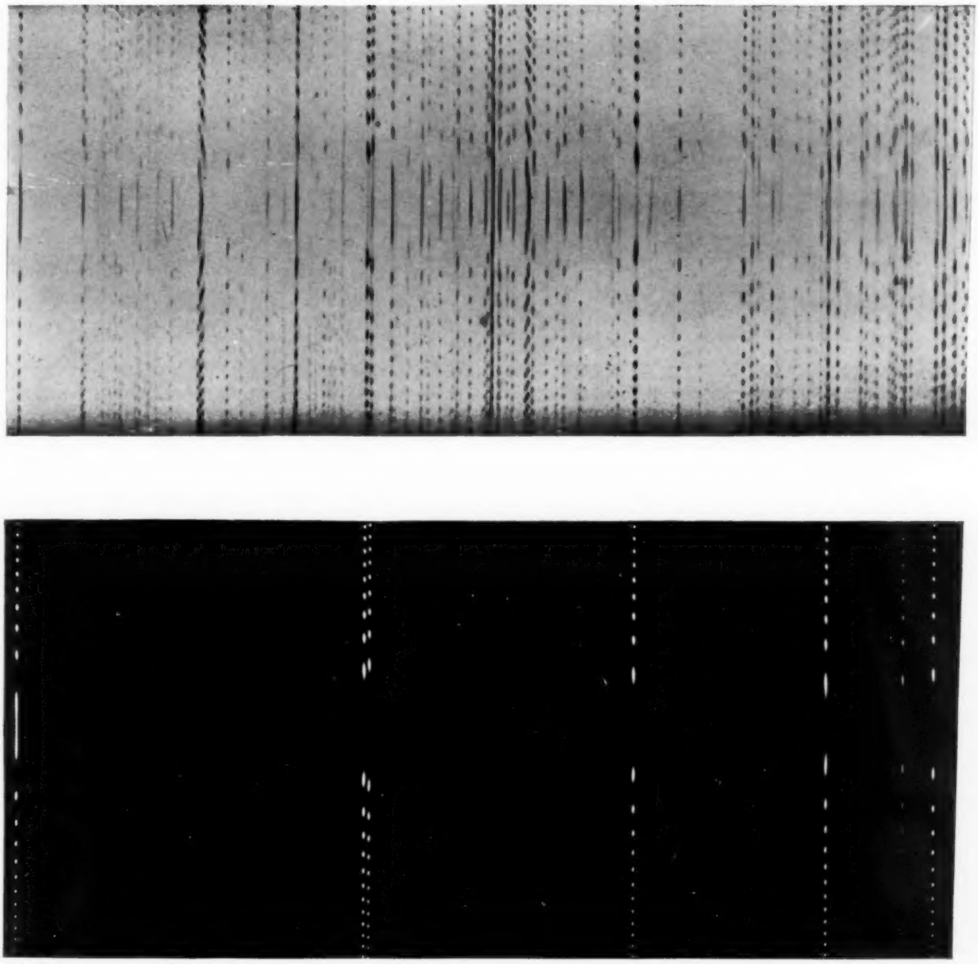
18-FOOT SPECTROGRAPH AND INTERFEROMETER OF THE SNOW HORIZONTAL TELESCOPE

PLATE IV



SIMULTANEOUS EXPOSURES WITH 75-FOOT SPECTROGRAPH ON SUN (*a*) AND ON IRON ARC (*b*). ENLARGEMENT ORIGINAL NEGATIVE, 1.25

PLATE V



λ 6065 λ 6252

INTERFEROMETER SPECTROGRAMS OF SUN (ABOVE) AND OF IRON ARC (BELOW)

TABLE VI

WAVE-LENGTHS AT CENTER OF SUN

minus

WAVE-LENGTHS FROM SOURCE IN VACUUM

(Unit for $\Delta\lambda$=0.001 A)

Section A — Iron Lines, Pressure Class *b*

Wave-Lengths: Sun's Center	Wave-Lengths: Vac.	$\Delta\lambda$: Obs.	$\Delta\lambda$: O−C	E.P.	Level in Km	Temperature Class
Violet: Solar Intensity 8–40; Mean 13.6						
3608.870....	859	+11	+ 3	1.007	500	I
3631.476....	463	13	5	0.954	600	I
3647.852....	843	9	1	.911	600	I
3709.257....	248	9	1	.911	400	II
3734.876....	866	10	2	.855	750	II
3749.497....	488	9	1	.911	....	II
3758.247....	234	13	5	.954	600	II
3763.805....	789	16	8	0.986	1000	II
3767.206....	193	13	5	1.007	1000	II
3787.893....	883	10	2	1.007	750	II
3795.014....	003	11	3	0.986	450	II
3815.853....	841	12	4	1.478	900	II
3820.438....	427	11	3	0.855	1200	II
3825.893....	882	11	3	0.911	1000	II
3827.834....	824	10	2	1.551	800	II
3834.235....	224	11	3	0.954	....	II
3840.449....	437	12	4	0.986	1200	II
3841.060....	049	11	3	1.601	1200	II
3849.979....	968	11	3	1.007	800	II
3878.029....	021	8	0	0.954	1200	II
3902.958....	947	11	3	1.551	900	II
3969.270....	259	11	3	1.478	....	II
4045.827....	814	13	5	1.478	1000	II
4063.607....	596	11	3	1.551	900	II
4071.751....	740	11	2	1.601	900	II
4132.069....	060	9	0	1.601	550	II
4143.880....	871	9	0	1.551	1000	I
4202.042....	031	11	2	1.478	600	I
4250.799....	790	9	0	1.551	700	II
4271.776....	764	12	3	1.478	800	II
4325.777....	764	13	4	1.601	900	II
4383.559....	548	11	2	1.478	1600	II
4404.763....	753	10	1	1.551	800	II
4415.137....	126	+11	+ 2	1.601	500	II
Means...	....	+11.0 ± 0.2	+2.7	1.245	840	....
Violet: Solar Intensity 6–7; Mean 6.2						
3585.720....	709	+11	+ 3	0.911	450	II
3621.468....	462	6	− 2	....	450	IV
3622.010....	005	+ 5	− 3	2.747	400	IV

TABLE VI—*Continued*

Wave-Lengths		Δλ		E.P.	Level in Km	Temperature Class
Sun's Center	Vac.	Obs.	O−C			
Violet: Solar Intensity 6–7; Mean 6.2—*Continued*						
3640.395....	390	+5	−3	2.716	400	IV
3651.475....	468	7	0	....	400	IV
3676.323....	312	11	+3	....	....	IV
3684.124....	111	13	+5	....	....	IV
3687.467....	458	9	+1	0.885	400	I
3689.470....	465	5	−3	....	400	IV
3716.452....	447	5	−3	....	400	IV
3724.387....	378	9	+1	....	400	III
3732.408....	397	11	+3	....	350	III
3743.370....	363	7	−1	0.986	600	II A
3753.622....	613	9	+1	2.167	500	III
3765.553....	541	12	+4	....	800	IV
3798.523....	513	10	+2	0.911	....	II
3799.560....	549	11	+3	0.954	750	II
3805.351....	344	7	−1	....	750	IV
3807.546....	539	7	−1	2.213	500	III
3865.535....	526	9	+1	1.007	900	II
3872.512....	504	8	0	0.986	700	II
3887.061....	051	10	+1	0.911	600	I
3956.688....	679	9	+1	2.681	500	III
3977.752....	743	9	+1	2.188	700	III
4005.256....	247	9	0	1.551	800	II
4067.990....	984	6	−2	....	450	III
4137.007....	002	5	−4	....	500	IV
4307.914....	906	8	−1	1.551	....	II
4442.351....	342	9	0	2.188	350	III
4447.730....	720	10	+1	2.213	450	III
4494.575....	568	7	−3	2.188	400	III
4602.951....	944	7	−3	1.478	350	I
4678.857....	852	+5	−5	....	400	V
Means...	....	+8.2	0.0	1.617	520	....
Violet: Solar Intensity 5						
3587.761....	751	+10	+2	2.839	350	IV
3603.211....	204	7	−1	2.681	300	IV
3623.193....	187	6	−2	2.394	400	IV
3625.148....	146	2	−6	2.820	500	IV
3649.512....	508	4	−4	....	400	IV
3650.286....	279	7	−1	2.422	400	IV
3659.525....	518	7	−1	2.443	....	IV
3695.057....	053	4	−4	....	400	IV
3707.053....	049	4	−4	2.985	400	IV
3760.057....	051	6	−2	....	500	III
3786.684....	677	7	−1	1.007	450	III
3790.100....	093	7	−1	0.986	750	II
3797.524....	516	8	0	....	....	III
3846.811....	803	+8	0	....	....	IV

TABLE VI—*Continued*

Wave-Lengths		Δλ		E.P.	Level in Km	Temperature Class
Sun's Center	Vac.	Obs.	O−C			
		Violet: Solar Intensity 5—*Continued*				
3876.053....	043	+10	+ 2	1.007	500	III
3888.526....	516	10	+ 2	1.601	500	II
3907.942....	936	6	− 2	....	500	IV
3909.839....	830	9	+ 1	....	500	III
3916.739....	735	4	− 5	....	....	IV
3918.653....	644	9	+ 1	....	....	IV
3925.653....	646	7	− 1	....	500	IV
3940.892....	881	11	+ 3	0.954	600	II
3949.963....	956	7	− 1	2.167	500	III
3951.174....	168	6	− 2	....	500	IV
3971.334....	325	9	+ 1	2.681	400	III
4021.872....	870	2	− 6	....	....	III
4062.451....	445	6	− 2	....	600	III
4066.986....	981	5	− 4	....	500	III
4098.185....	183	2	− 7	....	500	IV
4107.496....	492	4	− 5	....	450	III
4118.557....	549	8	− 1	....	....	IV
4123.755....	748	7	− 2	....	500	....
4134.687....	682	5	− 4	....	500	IV
4175.645....	640	5	− 3	....	500	III
4181.766....	758	8	− 1	....	....	III
4199.107....	098	9	0	....	....	III
4282.413....	405	8	− 1	2.167	700	III
4337.057....	049	8	− 1	1.551	600	II
4367.592....	580	12	+ 3	....	500	IV
4466.564....	553	11	+ 2	....	500	II
4531.160....	152	8	− 2	1.478	400	II
4691.429....	414	+15	+ 5	....	400	....
Means...	....	+ 7.1	− 1.3	2.011	490	....
		Violet: Solar Intensity 4				
3586.119....	112	+ 7	− 1	....	400	IV
3589.113....	106	7	− 1	0.855	350	III
3608.156....	148	8	0	2.839	....	IV
3630.356....	351	5	− 3	2.839	500	IV
3632.985....	978	7	− 1	....	400	IV
3637.874....	861	13	+ 5	2.927	350	IV
3643.628....	624	4	− 4	2.927	500	IV
3645.828....	821	7	− 1	....	400	IV
3647.429....	426	3	− 5	1.551	400	IV
3669.527....	522	5	− 3	....	....	IV
3677.319....	308	11	+ 3	....	400	IV
3678.870....	862	8	0	....	....	IV
3687.661....	655	6	− 2	....	400	III
3698.610....	608	+ 2	− 6	....	....	IV

TABLE VI—*Continued*

Wave-Lengths: Sun's Center	Wave-Lengths: Vac.	Δλ: Obs.	Δλ: O−C	E.P.	Level in Km	Temperature Class
Violet: Solar Intensity 4—*Continued*						
3702.038....	033	+5	−3	....	350	IV
3704.470....	463	7	−1	....	....	IV
3711.230....	225	5	−3	....	....	IV
3718.413....	407	6	−2	....	400	IV
3735.336....	326	10	+2	2.927	....	IV
3756.943....	939	4	−4	....	600	IV
3760.538....	532	6	−2	....	....	III
3774.834....	825	9	+1	2.213	....	IV
3794.349....	340	9	+1	....	500	III
3821.188....	180	8	0	....	500	IV
3833.319....	311	8	0	2.548	500	IV
3843.266....	258	8	0	....	....	IV
3850.828....	819	9	+1	0.986	....	II
3852.581....	574	7	−1	2.167	....	IV
3873.769....	762	7	−1	....	....	IV
3885.521....	511	10	+2	....	500	III
3891.936....	928	8	0	....	600	V
3893.404....	394	10	+2	....	600	IV
3906.756....	748	8	0	....	....	V
3909.670....	664	6	−2	3.269	500	V
3910.851....	846	5	−3	....	500	IV
3913.639....	634	5	−3	2.269	....	III
3918.326....	319	7	−1	....	....	....
3918.426....	418	8	0	....	....	IV
3925.950....	944	6	−2	....	600	IV
3947.540....	533	7	−1	2.819	....	IV
3948.787....	778	9	+1	....	....	IV
3952.617....	605	12	+4	....	600	IV
3956.465....	459	6	−2	....	....	IV
3981.777....	774	3	−5	2.716	....	III
3983.973....	961	12	+4	2.716	....	III
3994.121....	117	4	−4	....	....	IV
3997.403....	394	9	+1	2.716	600	III
3998.060....	056	4	−4	2.681	500	III
4017.161....	155	6	−3	....	400	III
4070.779....	772	7	−2	....	....	III
4076.639....	636	3	−6	....	400	IV
4078.368....	362	6	−3	....	....	IV
4085.015....	011	4	−5	....	500	IV
4085.319....	312	7	−2	2.747	....	IV
4100.749....	744	5	−4	0.855	....	II A
4114.453....	449	4	−5	....	450	IV
4120.215....	211	4	−5	....	400	IV
4126.193....	188	5	−4	....	400	IV
4127.615....	612	3	−6	....	550	IV
4132.910....	904	6	−3	1.601	500	III
4154.507....	503	4	−5	....	500	III
4170.914....	905	9	0	....	....	IV
4184.902....	895	+7	−2	....	500	III

TABLE VI—*Continued*

Wave-Lengths: Sun's Center	Wave-Lengths: Vac.	Δλ: Obs.	Δλ: O−C	E.P.	Level in Km	Temperature Class
			Violet: Solar Intensity 4—*Continued*			
4245.266....	260	+6	−3	....	500	III
4352.745....	737	8	−1	2.213	500	III
4369.781....	773	8	−1	....	500	III
4592.661....	655	6	−4	1.551	350	I
4630.130....	125	5	−5	2.269	300	....
4632.927....	915	12	+2	1.601	400	III
4638.019....	015	4	−6	....	350	IV
4643.472....	466	6	−4	....	....	....
4745.809....	803	6	−4	....	350	V
4772.824....	815	9	−1	1.551	350	III
5079.232....	225	7	−4	2.188	500	IV
5328.544....	532	12	+1	1.551	500	II
5701.559....	549	+10	−2	2.548	500	III
Means...	....	+6.8	−1.7	2.204	460	....
			Violet: Solar Intensity 3			
3587.432....	423	+9	+1	....	350	IV
3599.632....	625	7	−1	....	350	IV
3617.322....	316	6	−2	....	400	IV
3632.561....	557	4	−4	....	400	IV
3638.305....	298	7	−1	2.747	350	IV
3655.473....	464	9	+1	....	400	IV
3687.103....	099	4	−4	....	....	IV
3711.413....	408	5	−3	....	....	IV
3715.917....	913	4	−4	....	400	IV
3725.500....	496	4	−4	....	400	....
3727.100....	096	4	−4	2.927	400	IV
3730.394....	386	8	0	....	350	IV
3730.952....	945	7	−1	....	350	IV
3731.383....	374	9	+1	....	350	IV
3738.314....	307	7	−1	....	500	IV
3742.625....	621	4	−4	2.927	300	IV
3756.074....	069	5	−3	....	300	IV A
3768.036....	030	6	−2	2.213	....	IV
3773.701....	691	10	+2	....	500	IV
3776.463....	456	7	−1	....	500	IV
3777.458....	448	10	+2	....	500	IV
3778.705....	697	8	0	2.188	....	....
3781.193....	187	6	−2	....	....	IV
3785.954....	948	6	−2	....	....	IV
3789.186....	178	8	0	....	....	IV
3792.160....	156	4	−4	....	....	IV
3801.685....	680	5	−3	....	450	IV
3804.016....	012	4	−4	....	600	....
3808.736....	731	+5	−3	2.548	....	IV

TABLE VI—*Continued*

Wave-Lengths		Δλ		E.P.	Level in Km	Temperature Class
Sun's Center	Vac.	Obs.	O−C			
Violet: Solar Intensity 3—*Continued*						
3810.762....	758	+4	−4	....	....	IV
3816.347....	340	7	−1	2.188	400	IV
3836.339....	332	7	−1	....	....	IV
3839.265....	258	7	−1	....	500	IV
3859.225....	214	11	+3	....	....	III
3861.346....	341	5	−3	....	....	IV
3867.226....	219	7	−1	....	....	IV
3890.851....	844	7	−1	....	800	IV
3897.902....	896	6	−2	....	....	IV
3937.339....	330	9	+1	....	....	IV
3942.450....	443	7	−1	....	....	IV
3943.350....	342	8	0	2.188	....	IV
3944.900....	892	8	0	....	....	IV
3945.129....	119	10	+2	....	....	IV
3955.965....	958	7	−1	....	....	IV
3961.151....	147	4	−4	2.846	....	....
3964.528....	520	8	0	....	....	V
3966.075....	066	9	+1	1.601	....	III
3985.398....	393	5	−3	....	400	IV
3986.182....	176	6	−2	....	500	IV
3989.867....	859	8	0	2.269	....	V
3995.992....	987	5	−3	....	....	IV
4001.672....	666	6	−2	2.167	500	III
4003.773....	766	7	−1	....	....	V
4006.635....	631	4	−4	....	500	IV
4007.281....	277	4	−4	2.747	600	IV
4009.719....	715	4	−4	2.213	....	III
4044.619....	614	5	−4	....	500	IV
4067.282....	274	8	−1	....	....	III
4074.797....	792	5	−4	....	500	IV
4079.848....	846	2	−7	....	500	IV
4095.983....	975	8	−1	....	500	IV
4121.812....	807	5	−4	....	300	IV
4122.525....	520	5	−4	....	500	IV
4125.888....	884	4	−5	....	300	....
4156.812....	803	9	0	....	500	III
4182.389....	384	5	−4	....	450	IV
4207.135....	130	5	−4	....	400	IV
4208.612....	606	6	−3	....	350	V
4213.655....	650	5	−4	....	500	IV
4220.349....	344	5	−4	....	450	IV
4266.971....	968	3	−6	....	400	IV
4285.453....	446	7	−2	....	....	IV
4408.427....	418	9	0	....	450	III?
4422.578....	570	8	−1	....	....	III
4430.624....	617	7	−2	....	450	III
4443.203....	195	8	−1	....	....	III
4454.390....	383	7	−2	....	500	III
4517.537....	530	+7	−3	3.943	350	....

TABLE VI—*Continued*

Wave-Lengths: Sun's Center	Wave-Lengths: Vac.	Δλ: Obs.	Δλ: O−C	E.P.	Level in Km	Temperature Class
Violet: Solar Intensity 3—*Continued*						
4547.856....	850	+6	−4	....	400	V
4602.011....	005	6	4	1.601	350	....
4619.299....	293	6	4	....	350	IV
4683.570....	564	6	4	....	300	....
4710.292....	285	7	3	....	350	IV
4735.852....	846	6	4	....	250	....
4741.538....	531	7	3	....	300	V
4788.766....	757	9	1	....	300	....
4789.660....	653	7	3	....	400	V
4839.554....	549	5	5	....	300	....
4924.779....	773	6	4	2.269	350	V
5098.709....	701	8	3	2.167	400	IV
5198.718....	710	8	3	2.213	....	IV
5216.285....	276	9	2	1.601	350	II
5250.656....	648	8	3	2.188	400	IV
5307.371....	363	+8	−3	1.601	350	III?
Means...	....	+6.5	−2.2	2.334	420	....
Violet: Solar Intensity 2						
3637.001....	994	+7	−1	....	....	IV
3669.156....	150	6	−2	....	....	IV
3674.774....	765	9	+1	....	....	IV
3703.830....	824	6	−2	....	....	IV
3722.030....	026	4	−4	....	....	....
3728.673....	668	5	−3	....	....	IV
3757.460....	458	2	−6	....	....	IV
3778.517....	511	6	−2	2.985	....	IV
3781.940....	938	2	−6	....	....	....
3782.455....	450	5	−3	....	....	IV
3790.761....	756	5	−3	2.167	....	IV A
3791.511....	504	7	−1	....	....	....
3793.487....	481	6	−2	3.025	....	....
3793.878....	872	6	−2	....	....	IV
3802.287....	282	5	−3	....	....	....
3811.896....	892	4	−4	....	....	IV
3813.642....	638	4	−4	....	....	IV
3825.410....	404	6	−2	....	....	....
3827.582....	572	10	+2	....	....	IV
3830.766....	758	8	0	2.597	....	IV
3837.143....	133	10	+2	2.597	....	IV
3846.419....	412	7	−1	....	....	IV
3871.760....	750	10	+2	....	....	IV
3935.828....	815	13	+5	....	....	III
3967.433....	423	10	+1	....	....	IV
3970.401....	391	+10	+1	....	....	IV

TABLE VI—*Continued*

Wave-Lengths		Δλ		E.P.	Level in Km	Temperature Class
Sun's Center	Vac.	Obs.	O−C			
		Violet: Solar Intensity 2—*Continued*				
3976.870....	865	+5	−3	....	....	....
3990.381....	379	2	−6	....	....	V
3996.973....	968	5	−3	....	500	V
4000.468....	464	4	−4	....	....	V
4006.319....	314	5	−3	....	500	IV
4173.325....	320	5	−4	....	....	IV
4205.546....	543	3	−6	....	....	....
4225.964....	956	8	−1	....	....	IV
4226.433....	426	7	−2	....	....	IV
4229.522....	516	6	−3	....	....	....
4242.736....	730	6	−3	....	....	....
4246.094....	090	4	−5	....	400	V
4248.233....	228	5	−4	....	....	IV
4258.621....	614	7	−2	....	....	....
4265.268....	260	8	−1	....	....	....
4268.758....	747	11	+2	....	....	IV
4302.197....	190	7	−2	....	....	....
4309.040....	035	5	−4	....	....	....
4321.800....	798	2	−7	....	....	....
4343.707....	700	7	−2	....	400	....
4346.563....	557	6	−3	....	....	....
4348.949....	942	7	−2	....	....	....
4351.556....	548	8	−1	....	....	IV
4358.514....	505	9	0	....	....	IV
4367.914....	906	8	−1	1.601	....	III A
4373.570....	563	7	−2	2.548	400	....
4387.901....	895	6	−3	....	....	IV
4447.139....	133	6	−3	....	....	IV
4490.780....	773	7	−3	3.926	....	....
4547.027....	022	5	−5	1.551	....	....
4549.476....	470	6	−4	....	....	....
4574.730....	724	6	−4	2.269	350	....
4587.139....	132	7	−3	....	350	....
4595.367....	363	4	−6	....	350	....
4596.071....	063	8	−2	....	350	....
4635.857....	848	9	−1	....	300	....
4687.396....	389	7	−3	....	300	....
4721.002....	997	5	−5	....	300	....
4757.587....	580	7	−3	....	300	....
4771.714....	702	12	+2	2.188	....	....
4786.816....	810	6	−4	....	....	IV?
4800.655....	651	4	−6	....	300	....
4802.888....	883	5	−5	....	....	....
4838.523....	517	6	−4	3.402	350	....
5131.478....	473	5	−6	2.213	350	....
5242.501....	494	7	−4	....	250	IV
5329.998....	993	+5	−6	....	....	....
Means...	....	+6.3	−2.6	2.429	350	....

TABLE VI—*Continued*

Wave-Lengths		Δλ		E.P.	Level in Km	Temperature Class
Sun's Center	Vac.	Obs.	O−C			
Violet: Solar Intensity 1						
3709.539....	534	+ 5	− 3	....	....	....
3751.826....	820	6	− 2	....	....	....
3775.862....	857	5	− 3	....	....	....
3782.615....	612	3	− 5	....	....	....
3785.709....	706	3	− 5	....	....	....
3789.579....	572	7	− 1	....	....	....
3790.659....	656	3	− 5	....	....	....
3795.540....	532	8	0	....	....	....
3808.288....	284	4	− 4	....	....	....
3824.084....	077	7	− 1	2.577	....	IV
3845.702....	694	8	0	....	....	....
3931.131....	124	7	− 1	3.252	....	....
3932.639....	631	8	0	2.458	....	IV
3932.917....	917	0	− 8	....	....	....
3967.977....	964	13	+ 5	....	....	IV
3973.658....	655	3	− 6	....	....	V
4004.838....	833	5	− 4	....	....	....
4290.386....	382	4	− 5	....	....	....
4290.882....	870	12	+ 3	2.819	....	....
4338.273....	264	9	0	2.167	....	....
4432.577....	572	5	− 4	....	....	....
4439.891....	884	7	− 2	2.269	....	IV
4450.325....	321	4	− 6	2.269	....	....
4456.335....	331	4	− 6	....	....	....
4479.613....	609	4	− 6	3.671	....	IV
4480.147....	142	5	− 5	....	....	IV
4514.195....	189	6	− 4	....	....	....
4523.408....	403	5	− 5	....	....	....
4526.570....	563	7	− 3	....	....	....
4552.556....	547	9	− 1	....	....	....
4558.115....	108	7	− 3	....	....	....
4566.526....	520	6	− 4	....	....	....
4600.941....	937	4	− 6	....	....	....
4661.541....	537	4	− 6	....	....	....
4661.981....	975	6	− 4	....	....	....
4680.308....	298	10	0	1.601	....	....
4689.503....	495	8	− 2	....	....	....
4701.057....	050	7	− 3	....	....	....
4734.107....	100	7	− 3	....	....	....
4737.637....	633	4	− 6	....	....	....
4740.347....	343	4	− 6	....	....	....
4779.447....	439	+ 8	− 2	....	....	....
Means...	....	+ 5.9	− 3.1	2.565	....	....
Red: Solar Intensity 5–8; Mean 6						
6065.499....	488	+11	− 2	2.597	400	III
6136.631....	619	+12	− 1	2.433	400	III

TABLE VI—*Continued*

Wave-Lengths		Δλ		E.P.	Level in Km	Temperature Class
Sun's Center	Vac.	Obs.	O−C			
		Red: Solar Intensity 5–8; Mean 6—*Continued*				
6137.709....	698	+11	−2	2.577	400	III
6157.739....	727	12	1	....	....	V
6173.348....	338	10	3	2.213	....	III
6191.577....	564	13	0	2.422	300	II
6200.327....	318	9	4	2.597	....	IV
6213.443....	434	9	4	2.213	....	III
6215.157....	147	10	3	....	....	....
6219.294....	285	9	4	2.188	....	III
6230.742....	730	12	1	2.548	....	III
6252.572....	562	10	3	2.394	....	III
6265.148....	140	8	5	2.167	....	III
6297.808....	798	10	3	2.213	....	III
6318.036....	024	12	1	2.443	....	III
6335.345....	337	8	5	2.188	....	III
6358.695....	681	14	0	0.855	....	I A
6393.620....	607	13	1	2.422	....	III
6421.367....	357	10	4	2.269	....	III
6430.863....	854	9	5	2.167	....	III
6495.001....	988	13	1	2.394	....	II
6592.934....	923	11	2	2.716	....	III
6678.007....	997	+10	−4	2.681	....	III
Means...	....	+10.7	−2.6	2.319	375	....
		Red: Solar Intensity 2–4; Mean 3.2				
5956.709....	698	+11	−2	0.855	....	....
5975.356....	349	7	−6	4.529	....	V
6027.064....	055	9	−4	....	....	V
6127.918....	907	11	−2	....	....	....
6137.009....	995	14	+1	2.188	....	....
6165.369....	361	8	−5	....	....	....
6240.659....	651	8	−5	2.213	....	....
6270.237....	229	8	−5	2.846	....	....
6280.628....	619	9	−4	0.855	....	I A
6315.323....	309	14	+1	....	....	....
6322.701....	690	11	−2	2.577	....	III
6344.162....	155	7	−7	2.422	....	III
6355.043....	034	9	−5	2.833	....	III
6380.756....	748	8	−6	....	....	V
6475.640....	633	7	−7	2.548	....	IV
6518.384....	377	7	−7	2.819	....	....
6609.126....	120	6	−8	....	....	IV
6663.470....	452	18	+4	....	....	IV
6750.173....	160	+13	−1	....	....	IV
Means...	....	+9.7	−3.7	2.426	....	....

TABLE VI—*Continued*

Section B Iron Lines, Pressure Class *a*

Wave-Lengths: Sun's Center	Wave-Lengths: Vac.	Δλ: Obs.	Δλ: O−C	E.P.	Level in Km	Temperature Class
Solar Intensity 8–40; Mean 13.7						
3679.924....	914	+10	+ 2	0.000	500	I A
3705.578....	567	11	3	.051	750	I
3719.949....	937	12	4	.000	1500	I
3737.143....	132	11	3	.051	1500	I
3745.576....	562	14	6	.087	1500	I
3748.273....	263	10	2	.110	750	I A
3856.383....	372	11	3	.051	1200	I A
3859.924....	914	10	2	.000	1800	I
3886.296....	284	12	4	.051	1600	I
3899.721....	710	11	3	.087	1000	I
3906.492....	483	9	1	.110	750	I
3920.271....	260	11	3	.121	1000	I
3922.925....	913	12	4	.051	1200	I
3927.935....	922	13	4	.110	1000	I
3930.310....	298	+12	+ 4	0.087	1000	I
Means...	....	+11.3	+ 3.2	0.064	1140	....
Solar Intensity 4–7; Mean 5						
3649.308....	304	+ 4	− 4	0.000	400	I A
3733.332....	319	13	+ 5	.110	....	I A
3745.912....	901	11	+ 3	.121	....	I A
3878.582....	573	9	+ 1	.087	....	II
3895.669....	659	10	+ 2	.110	1200	I
4172.764....	749	15	+ 6	.954	600	II A
4174.919....	914	5	− 4	.911	500	II A
4375.946....	932	14	+ 5	.000	500	I
4427.319....	312	7	− 2	.051	600	I
4461.662....	654	8	− 1	.087	500	I
4489.750....	742	8	− 1	0.121	400	I A
4733.599....	594	5	− 5	1.478	400	I
5012.077....	072	5	− 6	0.855	500	I
5083.347....	342	5	− 6	.954	400	I
5107.459....	452	7	− 4	0.986	500	I
5107.653....	645	8	− 3	1.551	500	II
5150.854....	843	11	0	0.986	400	I
5171.612....	599	13	+ 2	1.478	600	II
5194.951....	943	8	− 3	1.551	400	I
5332.910....	902	8	− 3	1.551	350	I
5371.503....	492	11	0	0.954	500	I
5397.143....	130	13	+ 2	.911	800	I
5405.787....	777	10	− 1	.986	600	I
5429.708....	699	9	− 3	0.954	600	I
5434.536....	524	12	+ 1	1.007	500	I
5446.926....	917	+ 9	− 2	0.986	500	I

TABLE VI—*Continued*

Wave-Lengths		Δλ		E.P.	Level in Km	Temperature Class
Sun's Center	Vac.	Obs.	O−C			
		Solar Intensity 4–7; Mean 5—*Continued*				
5455.626....	612	+14	+ 2	1.007	500	I
5497.528....	519	9	− 3	1.007	500	I
5501.479....	467	12	0	0.954	400	I
5506.793....	781	+12	0	0.986	400	I
Means...	....	+ 9.6	− 0.7	0.834	516	....
		Solar Intensity 1–3; Mean 2.6				
4173.935....	927	+ 8	− 1	0.986	....	II A
4206.704....	698	6	3	.051	400	I A
4216.193....	187	6	3	.000	400	I
4258.326....	320	6	3	.087	400	I A
4291.475....	467	8	1	.051	....	I A
4348.949....	942	7	2	....	500	....
4389.256....	248	8	1	.051	400	II A
4435.158....	151	7	2	.087	....	II A
4939.695....	689	6	5	.855	350	I
4994.139....	133	6	5	0.911	500	I
5123.732....	725	7	4	1.007	400	I
5127.370....	363	7	4	0.911	300	I
5142.938....	932	6	5	0.954	400	I
5151.919....	914	+ 5	− 6	1.007	400	I
Means...	....	+ 6.6	− 3.2	0.533	404	....

TABLE VI—*Continued*

Section C — Iron Lines, Pressure Class $c5$, $d5$

Wave-Lengths		Δλ		E.P.	Level in Km	Temperature Class
Sun's Center	Vac.	Obs.	O−C			
		Solar Intensity 6–10; Mean 6.9				
4187.049....	043	+ 6	− 3	2.439	600	III
4191.439....	435	4	− 5	2.548	550	III
4233.613....	607	6	− 3	2.471	400	III
4235.951....	942	9	0	2.415	650	III
4250.132....	124	8	− 1	2.458	700	III
4260.488....	479	9	0	2.389	500	III
4271.166....	158	8	− 1	2.439	800	III
4736.783....	777	6	− 4	3.197	400	II?
4890.765....	760	5	− 5	2.863	600	III
4891.504....	496	8	− 2	2.839	600	III
4919.000....	992	8	− 3	2.853	400	III
4920.516....	507	9	− 1	2.820	500	III
4957.612....	598	14	+ 3	2.796	500	III
5232.954....	942	12	+ 1	2.927	400	III
5266.565....	556	9	− 2	2.985	350	IV
5283.631....	621	10	− 1	3.227	350	IV
5324.193....	181	12	+ 1	3.197	400	IV
5339.939....	932	7	− 4	3.252	250	V
5569.633....	620	13	+ 1	3.402	500	IV
5586.773....	757	16	+ 4	3.354	750	IV
5615.664....	645	+19	+ 7	3.318	500	IV
Means...	....	+ 9.4	− 0.9	2.862	510	....
		Solar Intensity 2–5; Mean 3.8				
3667.262....	261	+ 1	− 7	....	500	IV
3739.531....	523	8	0	....	....	IV
3855.853....	844	9	+ 1	....	....	....
3920.845....	835	10	+ 2	....	....	....
3948.111....	103	8	0	....	600	....
3963.117....	106	11	+ 3	....	....	V
4024.734....	732	2	− 7	....	....	V
4063.290....	284	6	− 3	3.354	....	....
4084.503....	497	6	− 3	3.318	400	IV
4136.530....	510	20	+11	....	500	....
4154.815....	810	5	− 4	....	500	IV
4157.790....	787	3	− 6	....	400	IV
4195.342....	335	7	− 2	....	....	IV
4196.216....	216	0	− 9	....	....	IV
4222.223....	216	7	− 2	2.439	500	III
4225.463....	457	6	− 3	....	....	IV
4227.442....	433	9	0	....	....	III
4238.031....	023	8	− 1	....	500	IV
4238.818....	814	4	− 5	....	....	IV
4247.434....	431	3	− 6	....	400	III
4299.252....	239	+13	+ 4	2.415	....	III

TABLE VI—*Continued*

Wave-Lengths		Δλ		E.P.	Level in Km	Temperature Class
Sun's Center	Vac.	Obs.	O−C			
Solar Intensity 2–5; Mean 3.8—*Continued*						
4388.416....	408	+8	−1	....	400	IV
4401.300....	289	11	+2	3.587	....	....
4446.845....	836	9	0	3.671	350	....
4469.385....	380	5	−5	....	400	IV
4484.229....	225	4	−6	3.587	350	IV
4525.148....	143	5	0	....	....	IV
4531.634....	629	5	0	3.912	350	....
4598.127....	119	8	−2	3.269	300	....
4607.655....	653	2	−8	3.252	350	V
4613.215....	207	8	−2	3.278	....	V
4625.054....	051	3	−7	3.227	350	IV
4637.512....	507	5	−5	3.269	350	IV
4707.287....	278	9	0	3.227	....	IV
4859.749....	745	4	−6	2.863	350	III
4882.150....	147	3	−7	3.402	350	....
4938.822....	816	6	−4	2.863	350	IV
4946.397....	390	7	−4	3.354	350	IV
4950.113....	109	4	−7	3.402	350	....
4957.309....	300	9	−1	2.839	....	III
4966.097....	092	5	−5	3.318	350	V
4982.509....	504	5	−6	....	300	....
4983.861....	852	9	−2	....	300	V
4985.261....	257	4	−7	....	350	V
5001.872....	867	5	−6	....	400	V
5014.951....	945	6	−5	....	350	V
5022.243....	239	4	−7	....	350	V
5027.131....	131	0	−11	....	350	V
5068.773....	770	3	−8	....	500	V
5137.395....	383	12	+1	....	350	V
5139.263....	256	7	−4	....	350	IV
5139.475....	464	11	0	....	500	IV
5191.467....	455	12	+1	....	500	IV
5192.355....	345	10	−1	2.985	500	IV
5215.190....	180	10	−1	3.252	300	IV
5217.398....	390	8	−3	3.197	300	V
5229.862....	852	10	−1	3.269	400	V
5263.316....	309	7	−4	3.252	350	V
5281.800....	793	7	−4	3.025	350	IV
5302.309....	301	8	−3	3.269	350	V
5466.407....	399	8	−4	....	300	....
5473.912....	903	9	−3	4.136	450	....
5476.578....	566	12	0	4.086	....	IV
5576.101....	090	11	−1	3.415	500	IV
5624.559....	542	17	+5	3.402	400	IV
5638.274....	262	12	0	4.202	350	V
5753.135....	128	7	−5	....	400	V
5775.091....	082	+9	−3	4.202	....	....
Means...	....	+7.2	−2.8	3.322	390	....

OBSERVATIONS OF IRON LINES AT THE SUN'S EDGE

The advantage of observations at the limb is the elimination of Doppler shifts produced by radial currents in the sun's atmosphere. At the center of the image the full force of radial currents is effective, while at a distance from the center of 98.5–99 per cent of the radius, where the limb observations were made, the effect of ascending and descending currents is inappreciable. Such measures, on the other hand, are subject to some uncertainty because of a possible limb effect. The spectral lines for this region present a different appearance from those observed at the sun's center, which might lead to the expectation of some influence on the wave-lengths. As will be seen later, the mean differential effect between limb and center which can be attributed to this cause is very small for the lines measured.

TABLE VII

SUMMARY OF DATA FOR IRON LINES IN TABLE VI

(Unit for $\Delta\lambda = 0.001$ A)

Class	No. of Lines	Mean λ	$\Delta\lambda$ Mean Obs.	$\Delta\lambda$ O−C	Equiv. Veloc.	E.P.	Evershed Effect	Level in Km	Solar Intensity
					km/sec.		km/sec.		
b, Violet..	34	3943	+11.0	+2.7	+0.21 dn	1.245	0.03 out	840	13.6
	33	3917	8.2	0.0	.00	1.617	.45 out	520	6.2
	42	3974	7.1	−1.3	− .10 up	2.011	.57 out	490	5
	76	4026	6.8	−1.7	− .13 up	2.204	.63 out	460	4
	95	4106	6.5	−2.2	− .16 up	2.257	.69 out	420	3
	73	4219	6.3	−2.6	− .19 up	2.429	.75 out	350	2
	42	4269	5.9	−3.1	− .22 up	2.565	.84 out	Low	1
b, Red...	23	6295	10.7	−2.6	− .12 up	2.319	.62 out	375	6
	19	6311	9.7	−3.7	− .18 up	2.426	.76 out	325	3
a........	15	3830	11.3	+3.2	+ .25 dn	0.064	.05 in	1140	13.7
	31	4856	9.6	−0.7	− .04 up	0.834	.41 out	515	5
	14	4629	6.6	−3.2	− .21 up	0.533	.66 out	400	2.6
*c*5, *d*5....	21	4865	9.4	−0.9	− .06 up	2.862	.33 out	510	6.9
	68	4728	+ 7.2	−2.8	−0.18 up	3.322	0.58 out	390	3.8

The solar rotation does not enter as a disturbing factor because the tabulated displacements are the means for points in the same heliographic latitude at opposite limbs. The effect of solar rotation is therefore completely eliminated. The influence of random hori-

TABLE VIII

WAVE-LENGTHS AT EDGE OF SUN

minus

WAVE-LENGTHS OF SOURCE IN VACUUM

(Unit for $\Delta\lambda$=0.001 A)

Iron Lines of Pressure Classes *a* and *b*

Wave-Lengths		$\Delta\lambda$		Class
Sun's Edge	Vacuum	Obs.	O−C	
Solar Intensity 8–25; Mean 11.9				
3787.893	883	+10	+ 2	*b*
3795.014	004	10	2	*b*
3815.852	841	11	3	*b*
3820.438	429	9	1	*b*
3825.894	883	11	2	*b*
3827.833	824	9	1	*b*
3834.235	224	11	3	*b*
3840.448	437	11	3	*b*
3841.060	049	11	3	*b*
3849.979	969	10	2	*b*
3856.384	372	12	3	*a*
3859.923	914	9	0	*a*
3878.031	021	10	2	*b*
3886.296	284	12	4	*a*
3899.721	710	11	2	*a*
3902.956	947	9	1	*b*
3906.495	483	+12	+ 4	*a*
Means	....	+10.4	+ 2.2	....
Solar Intensity 5–7; Mean 5.8				
3790.105	095	+10	+ 2	*b*
3797.524	517	7	− 1	*b*
3798.524	513	11	+ 3	*b*
3799.560	549	11	+ 3	*b*
3805.355	345	10	+ 2	*b*
3807.549	540	9	+ 1	*b*
3824.455	444	11	+ 3	*a*
3846.811	804	7	− 1	*b*
3865.535	526	9	+ 1	*b*
3872.513	504	9	+ 1	*b*
3876.056	044	12	+ 4	*b*
3887.061	051	10	+ 2	*b*
3888.527	517	10	+ 2	*b*
3895.669	659	10	+ 2	*a*
5049.837	825	12	+ 1	*a*
5110.423	413	10	− 1	*a*
5171.610	599	11	0	*a*
5227.204	190	14	+ 3	*a*
5371.508	492	+16	+ 5	*a*

TABLE VIII—*Continued*

Wave-Lengths		Δλ		Class
Sun's Edge	Vacuum	Obs.	O−C	
Solar Intensity 5–7; Mean 5.8—*Continued*				
5397.148	130	+18	+7	*a*
5405.794	777	17	+6	*a*
5429.713	699	14	+4	*a*
5434.543	524	19	+9	*a*
5446.931	917	14	+3	*a*
5497.534	519	15	+3	*a*
5501.478	467	11	−1	*a*
5506.796	781	+15	+3	*a*
Means	....	+11.8	+2.4	....
Solar Intensity 3–4; Mean 3.4				
3789.186	179	+7	−1	*b*
3794.350	341	9	+1	*b*
3801.690	682	8	0	....
3804.021	014	7	−1	....
3810.766	760	6	−2	*b*
3816.351	341	10	+2	....
3821.190	181	9	+1	*b*
3833.323	312	11	+3	*b*
3836.340	333	7	−1	....
3839.269	259	10	+2	*a*
3850.830	820	10	+2	*b*
3852.584	575	9	+1	....
3859.225	214	11	+3	*b*
3861.351	342	9	+1	*b*
3867.226	220	6	−3	*b*
3873.773	764	9	+1	*b*
3885.522	512	10	+2	*b*
3890.854	845	9	+1	*b*
3891.937	929	8	0	*b*
3893.406	395	11	+3	*b*
3897.903	897	6	−2	*b*
4994.146	133	13	+2	*a*
5041.085	074	11	0	*a*
5041.773	758	15	+4	*a*
5051.651	637	14	+3	*a*
5079.237	226	11	+1	*b*
5079.757	742	15	+4	*a*
5083.356	341	15	+4	*a*
5098.715	704	11	0	*b*
5107.470	452	18	+7	*a*
5107.659	645	14	+3	*a*
5123.742	723	19	+9	*a*
5141.756	748	8	−2	*b*
5142.545	541	4	−6	*b*
5142.943	933	+10	−1	*a*

TABLE VIII—*Continued*

Wave-Lengths: Sun's Edge	Wave-Lengths: Vacuum	Δλ: Obs.	Δλ: O−C	Class
Solar Intensity 3–4; Mean 3.4—*Continued*				
5150.860.......	843	+17	+ 6	*a*
5151.926.......	913	13	+ 2	*a*
5198.731.......	712	19	+ 8	*a*
5216.294.......	277	17	+ 6	*a*
5250.666.......	649	17	+ 6	*a*
5254.968.......	953	15	+ 4	*a*
5307.375.......	364	11	0	*a*
5322.055.......	046	9	− 2	*b*
5332.920.......	900	20	+ 9	*a*
5365.417.......	402	15	+ 4	*a*
5379.585.......	575	10	0	*b*
5398.295.......	282	13	+ 3	*b*
5455.634.......	612	+22	+10	*a*
Means.....	....	+11.6	+ 2.0	....
Solar Intensity 0–2; Mean 1.5				
3789.580.......	571	+ 9	+ 1	*b*
3793.484.......	479	5	− 3	....
3793.882.......	873	9	+ 1	....
3795.541.......	532	9	+ 1	....
3797.954.......	949	5	− 3	*b*
3801.815.......	805	10	+ 2	....
3802.288.......	284	4	− 4	....
3808.293.......	288	5	− 3	....
3813.645.......	639	6	− 2	....
3824.082.......	075	7	− 1	....
3825.414.......	405	9	+ 1	....
3830.768.......	758	10	+ 2	....
3837.146.......	133	13	+ 5	....
3845.698.......	693	5	− 3	....
3846.423.......	413	10	+ 2	*b*
3871.761.......	751	10	+ 1	*b*
3893.932.......	925	7	− 1	*b*
3897.460.......	450	10	+ 2	*b*
5028.140.......	129	11	0	*b*
5029.630.......	621	9	− 2	*b*
5065.207.......	199	8	− 3	*b*
5131.485.......	475	10	− 1	*a*
5235.402.......	390	12	+ 1	*b*
5242.510.......	493	17	+ 7	*a*
5247.068.......	049	19	+ 9	*a*
5250.228.......	209	19	+ 8	*a*
5251.982.......	968	14	+ 3	*b*
5288.541.......	530	11	0	*b*
5298.794.......	786	8	− 3	*b*
5326.157.......	151	6	− 5	*b*
5330.008.......	993	+15	+ 3	*a*

TABLE VIII—*Continued*

Wave-Lengths		Δλ		Class
Sun's Edge	Vacuum	Obs.	O−C	
Solar Intensity 0–2; Mean 1.5—*Continued*				
5332.678.......	670	+8	−3	*b*
5403.835.......	820	15	+3	*b*
5436.602.......	591	11	0	*b*
5464.292.......	283	9	−2	*b*
5532.761.......	749	12	0	*b*
5535.431.......	416	15	+3	*b*
5546.518.......	509	9	−3	*b*
5553.591.......	583	8	−4	*b*
5562.717.......	709	8	−3	*b*
5567.406.......	398	+8	−3	*b*
Means.....	....	+9.9	0.0	....

zontal currents is reduced to a minimum by combining measures in different latitudes and on photographs made on many different days.

The wave-lengths of the separate lines at the edge and in vacuum are entered in the first and second columns, respectively, of Table VIII. The displacements, λ edge *minus* λ vacuum, are entered as

TABLE IX

Summary of Observations at the Sun's Edge
Iron Lines—Classes *a*, *b*

(Unit for Δλ=0.001 A)

No. of Lines	Wave-Length	Δλ		Level in Km	Int.
		Observed	O−C		
17........	3849	+10.4	+2.2	840	11.9
27........	4567	11.8	+2.4	520	5.8
48........	4600	11.6	+2.0	440	3.4
41........	4671	+9.9	0.0	350	1.5

Δλ in the third column, and the residuals, displacement observed *minus* displacement calculated from general relativity, in the fourth column. The results are summarized in Table IX.

DISCUSSION

From the point of view of general relativity it is significant that the displacement at the center and edge of the sun for every line in Tables VI and VIII is toward longer wave-length. For convenience, the discussion of this material is based on the summaries in Tables VII and IX.

At the center, for the region λ 3917, the average displacement to the red of lines of medium level, class *b*, intensity 6, is that predicted by general relativity. For lines of higher level it is greater, and for lines of lower level it is less than the calculated magnitude, the discrepancy in the latter case increasing systematically with decrease of level for each pressure class, as shown in the fifth column of Table VII. The relative levels are given by the horizontal velocities of outflow of the gases of the reversing layer from the spot vortex in the eighth column, the lowest level corresponding to the highest outward velocity,[1] and by the heights and intensities in the ninth and tenth columns.

At the limb the average displacement for low-level lines, mean intensity 1.5, originating at 350 km, is in exact agreement with Einstein's theory. For the next three levels, extending to 850 km, the deviations are sensibly constant and, in the mean, equal +0.0022 A. For the four groups observed at the limb, including 133 lines, the mean deviation from the theoretical displacement predicted by relativity is +0.0015 A.

The progression with level shown by the displacements at the center (Table VII) is that brought to light in section *e*, page 204, as something independent of relativity and there attributed to the action of radial currents. Such currents, however, cannot explain the total displacements between the sun and the arc, which are always positive. To do so would require the very improbable assumption of radial currents descending at all levels. An even more conclusive reason is that the sun-*minus*-vacuum displacements at the limb (Table IX), where radial currents can have no effect on the position of the line, are not zero. Practically speaking, the progression which is so conspicuous at the center disappears at the limb, which greatly strengthens the hypothesis that radial currents exist; but at the limb

[1] St. John, *Mt. Wilson Contr.*, No. 69; *Astrophysical Journal*, **37**, 342, 1913.

there remains a mean positive displacement which, on the whole, is greater even than that at the center of the disk. Hence at the limb, some cause other than radial currents is also operative in producing displacements.

The universal positive displacement of lines at all levels, both at center and limb, was formerly attributed to a higher pressure in the sun than in the vacuum or open arc, but the pressure is now known to be practically zero in the atmospheres of the sun and stars. The red displacements cannot now be ascribed to increase of pressure over that in the arc.

Differences in the character of spectral lines at the center and the limb, as already suggested, raise a question as to the existence of a true limb effect. Such an effect may well account for the small systematic difference of $+0.0015$ A shown by the measures at center and limb after allowing for the progression attributed to radial currents, but leaves the bulk of the relatively large red displacement unexplained. The only other known agency which can account for this is the gravitational displacement of relativity. Allowance for this leaves, for the sun's center, the progressive sequence of residuals $O-C$ in the fifth column of Table VII, positive at high levels and negative at low levels, which are attributed, respectively, to descending and ascending currents. Ascending convection currents are to be expected at low levels; at high levels Milne's and Merfield's suggestion of the equivalent of downward currents is confirmed by the behavior of lines of very high level (Table V). The hypothesis of vertical currents requires zero effect at some intermediate level. For the center of the sun, relativity fixes this level at that for lines of group *b* of mean solar intensity 6 (see Table X), which by pure chance was originally selected to represent the medium level.

At the limb, the corresponding residuals in the fifth column of Table IX are practically constant. Here there is no question of radial currents, and the small mean difference, in so far as real, is provisionally regarded as a true limb effect.

One important test at least can immediately be applied to these conclusions with the aid of the present data. The red displacement of relativity is proportional to wave-length. Residuals found for lines of the same level, by allowing for a displacement varying in this

manner, must correspond to radial motions which are independent of wave-length. Table XI gives such a comparison for two large groups of lines having the mean wave-lengths 4026 and 6295 A. Judged by the velocity of outflow from spots (third column, Table XI), the levels for the two groups are the same. The wave-lengths, total displacements, and residual displacements have the same ratio,

TABLE X

LEVEL OF LINES GIVING THE EINSTEIN DISPLACEMENT

(Unit for Residuals = 0.001 A)

Lines	Int.	Δλ		Equiv. Vel.	Evershed Effect	Level	No. of Lines
		Obs.	O−C				
				km/sec.	km	km	
Fe class *b*	6.2	+8.2	0.0	0.00	0.48 out	525	32
Fe class *a*	5	+9.6	− .7	− .04 up	.41 out	515	30
Ti	4.2	+9.1	+0.4	+0.03 dn	0.45 out	520	12
Means...	....	+9.0	−0.1	0.00	0.45 out	520	....

TABLE XI

DISPLACEMENTS OF LINES AT SAME LEVEL BUT IN DIFFERENT SPECTRAL REGIONS

No. Lines	Mean λ	Velocity of Outflow	Δλ		Equivalent Velocity
			Sun−Vac.	O−C	
		km/sec.			km/sec.
76..........	4026	0.63	0.0068 A	−0.0017 A	0.13 up
23..........	6295	0.62	0.0107	−0.0026	0.12 up
Ratio....	1.56	....	1.57	1.53	....

as they should; and, finally, the upward velocities in the last column, which are equivalent to the negative residuals in the fifth column, are equal, in accordance with what was to have been expected.

It should be noted that convection currents or other conditions producing similar effects are not arbitrarily introduced into the picture for the purpose of explaining the deviations of the observed displacements from the predictions of relativity. Instead, they are interpretations of the progression in the displacements, appearing in the stars as well as the sun, which is independent of relativity.

The particular interpretation adopted for the displacements which depend upon difference in level is not important in the present discussion, but their presence and effect should be taken into account in any consideration of line-displacement, as they were for the first time in my paper at the Los Angeles meeting of the American Association for the Advancement of Science,[1] September 23, 1923; again in *Monthly Notices of the Royal Astronomical Society*, December, 1923; and later in a paper before the National Academy of Sciences, April, 1924.[2] The displacements of low-level lines to the violet with respect to lines of medium level appear, however, to find an adequate explanation in currents rising from or through the photosphere; and of high-level lines to the red, in an excess of absorption on the red edge of the lines. The practical disappearance of these relative displacements at the limb strongly supports the interpretations adopted here.

In the main, the deviations from relativity to be expected in the case of lines observed at the sun's center will be negative, for 99 per cent of the 20,000 lines in Rowland's tables are lower in level than those of class *b*, intensity 6, which fulfil the prediction of Einstein. Only about 200 solar lines originate above the medium-level lines. These give positive residuals when observed and calculated displacements are compared.

The discussion of the measures at the sun's center up to this point has been based upon the 395 *Fe* lines of class *b*. Class *a* includes the *Fe* lines of lowest energy-level, the ultimate lines, and should represent the highest level reached by iron vapor in the sun's atmosphere. This is confirmed by the data in the seventh and eighth columns of Table VII. The highest-level lines of group *b* (840 km), mean intensity 13.6, show outflow, while the highest-level lines of group *a* (1140 km), mean intensity 13.7, show inflow around spots. The larger positive residual for group *a*, fifth column, and the greater downward velocity, sixth column, are a logical consequence of this difference in level, which itself is a consequence of the differences in excitation potentials. The two groups consist of lines

[1] *Publications of the American Astronomical Society*, **5**, 84, 1923.

[2] *Mt. Wilson Communications*, No. 96; *Proceedings of the National Academy of Sciences*, **12**, 65, 1926.

in the same spectral region and of the same mean solar intensity. This would seem to eliminate any possible effects of an asymmetry varying with intensity or wave-length[1] and to leave difference in level as the effective condition.

The results for groups $c5$ and $d5$, because of pole-effect and asymmetry in the arc, would not have high weight if they stood alone; but their agreement with group b shows that pole-effect is practically eliminated. The close agreement between measures by Fabry and Buisson[2] and the present measures on the same eight lines of these groups adds further weight to them:

Fabry and Buisson, λ sun$-\lambda$ arc in vacuum........ +0.0075 A
Present measures, λ sun$-\lambda$ arc in vacuum.......... +0.0071

SUPPLEMENTARY EVIDENCE FROM OTHER ELEMENTS

A large number of measures have also been made at the sun's center for elements other than iron. These observations, which fully confirm the results and conclusions stated above, are here summarized for each of the elements in question.

Silicon.—The silicon lines are similar to the iron lines in behavior. This is illustrated in Table XII where the high-level lines are at the top and the low-level lines at the bottom.

Titanium.—The titanium spectrum has recently been measured in vacuum by Brown[3] and by Crew.[4] The lines of neutral titanium, Table XIII, show results consistent with the behavior of the iron lines and add the important fact that even very low-level lines, intensity 000–00, are displaced to the red by nearly 0.006 A. The march of excitation potential in the sixth column compared with level in the seventh column brings out clearly what was shadowed forth for iron in the seventh column of Table VII, namely, that lines of low energy-level are high-level lines in the sun. The titanium lines are identified in multiplets, and the excitation potential is known for each. Relatively few *Fe* lines are so identified. Nevertheless, the same relation between energy-level and height above the photosphere was evident for iron, but not so perfectly shown as for the titanium lines. Its emergence under the not very favorable condi-

[1] Burns and Kiess, *Publications of the Allegheny Observatory*, **6**, 139 (No. 8), 1927.

[2] *Astrophysical Journal*, **31**, 113, 1910. [3] *Ibid.*, **56**, 53, 1922. [4] *Ibid.*, **60**, 108, 1924.

tions for iron indicates that the correlation represents a real relationship between the energy-level of the atom and the height at which atoms in a particular state of transition are present in detectable quantity. Excitation potentials are therefore properly included in section *d* with other criteria for determining the relative levels of Fraunhofer lines. They may be used, however, only for the lines of a given element taken in the large.

Manganese.—The arc spectrum of manganese has many unsymmetrical lines with large pole-effect, and, in general, the quality of the lines is not so high as for lines of the same pressure groups of

TABLE XII

NEUTRAL SILICON AND IRON AT SAME LEVEL

(Unit for $\Delta\lambda = 0.001$ A)

No.	Mean λ	Δλ Sun−Vac.	Δλ O−C	Equivalent Velocity	Level	Intensity
				km/sec.	km	
1 *Si*	3905	+11	2.7	+0.21 dn	800	12
34 *Fe*	3943	11	2.7	+ .20 dn	840	13.6
5 *Si*	5675	9.4	2.6	− .14 up	325	2
42 *Fe*	6305	+10.2	3.2	−0.15 up	350	4.5

iron. Monk[1] has made a short series of measures in vacuum. For these the sun-*minus*-vacuum displacements, as shown by the third section of Table XIV, yield results in agreement with those of iron at like level.

For *Fe* and *Mn* at the same level, as shown by the velocity of outflow from spots, the negative residuals give upward currents of the same velocity (top of third section, Table XIV). The longer the wave-length, the deeper we see into the sun's atmosphere. When *Mn* lines λ 5453 are compared with *Fe* lines λ 4269, the negative residuals for manganese show an upward current of higher velocity corresponding to its lower level (bottom of third section, Table XIV).

Cyanogen.—Lines in the 3883 band have been used by several investigators—Schwarzschild, St. John, Grebe and Bachem, and

[1] *Astrophysical Journal*, 57, 222, 1923.

Evershed—in the study of the gravitational displacement of solar spectrum lines. The choice of lines for this purpose was made at a time when the pressure in the sun's atmosphere was thought to be of the order of 5–7 atmospheres. As band lines show no appreciable pressure shift, their use seemed to eliminate one variable. High pressure in the sun was then the accepted interpretation of the displacements to the red, now attributed to the sun's gravitational field.[1] The choice was unfortunate because of the high density of line-distribution, the overlapping of series, and the probability of undetected blends.

TABLE XIII

NEUTRAL TITANIUM

(Unit for $\Delta\lambda$=0.001 A)

No. of Lines	Mean λ	$\Delta\lambda$		Equiv. Veloc.	E.P.	Level	Solar Intensity
		Mean Obs.	O−C				
				km/sec.		km	
12.....	4110	+9.1	+0.4	+0.03 dn	0.324	520	4.2
32.....	4604	9.7	+ .1	.00	0.765	390	3
58.....	4496	9.2	−0.3	− .02 up	1.177	385	2
46.....	4537	8.1	−1.5	− .10 up	1.586	380	1
66.....	4770	7.0	−3.1	− .19 up	1.774	Low	0
188.....	4864	+5.9	−4.4	−0.27 up	1.934	Very low	000–00

My original investigation was confined to some 40 lines and gave negative results. In view of later work on the complete band, these lines might be called the "Forty Thieves." The present investigation includes the whole band, 515 lines, for which results are given in the left half of Table XV. It is assumed that random errors introduced by faulty measures, blends, and overlapping series are as likely to be positive as negative, and that their effect will be practically eliminated from the mean. As a check on the validity of this assumption, an excellent fourth-order spectrogram of the band was sent to R. T. Birge, of the University of California, for examination of the structure of the band, with special reference to the overlapping of series. As a result of his study of the plate, he selected a list of 184 lines which he considered especially suited to measurement. The results for these are given in the right half of Table XV.

[1] Birge, *ibid.*, **59**, 45, 1924.

TABLE XIV

MANGANESE LINES; MIXED CLASSES

λ Sun's Center *minus* λ Arc in Vacuum

(Unit = 0.001 A)

Wave-Lengths		Δλ		Class	E.P.	Level in Km	Solar Int.
Sun's Center	Vac.	Observed	O−C				
Solar Intensity 2–7; Mean 3.9							
4490.091........	079	+12	+ 2	*c*	2.940	400	3
4502.226........	220	6	− 4	*c*	2.907	300	2
4709.720........	711	9	− 1	*b*	2.876	350	2
4739.115........	106	9	− 1	*b*	2.928	350	3
4754.041........	037	4	− 6	*d*	2.272	400	7
4761.530........	518	12	+ 2	*b*	2.940	350	3
4762.377........	367	10	0	*b*	2.876	400	5
4765.866........	855	11	+ 1	*b*	2.928	300	3
4766.425........	423	2	− 8	*b*	2.907	350	4
4783.426........	426	0	−10	*d*	2.288	500	6
4823.516........	512	+ 4	− 6	*d*	2.309	750	5
Means......	....	+ 7.2	− 2.8	....	2.743	405	3.9
Solar Intensity 00–1; Mean 0							
5394.678........	672	+ 6	− 5	*a*	0.000	....	{1, 1
5399.476........	480	− 4	−15	*d*	3.836	....	1
5420.360........	353	+ 7	− 4	....	2.133	....	{0, 0
5432.550........	544	+ 6	− 6	*a*	0.000	....	1
5470.640........	640	0	−12	*b*	2.154	....	{0, 0
5516.785........	772	+13	+ 1	*b*	2.169	....	{0, 0
5537.764........	753	+11	− 1	....	2.177	....	{00, 00
Means......	....	+ 5.6	− 6.0	....	1.781	....	0

Comparison with Iron

Element	No. of Lines	Mean λ	Δλ Obs. Mean	Δλ O−C	Equiv. Veloc.	Evershed Effect	Level in Km	Solar Int.
					km/sec.	km/sec.		
Fe.......	68	4728	+7.2	−2.8	−0.18 up	0.58 out	390	3.8
Mn......	11	4714	7.2	2.8	.18 up	.60 out	405	3.9
Fe.......	42	4269	5.9	3.1	.22 up	0.84 out	Low	1
Mn......	7	5453	+5.6	−6.0	−0.33 up	....	Lower	0

The 43 lines in my original paper are included among the 515 lines. Their remeasurement agrees well with the original measures, which failed to show displacements to the red in agreement with the Einstein theory of gravitation. Their influence, however, is counteracted in the final mean, based upon the far greater number of lines. The results for the center of the sun are reduced to the limb by adding 0.0026 A, the mean of the limb-*minus*-center displacement for *CN* lines found by Adams and of more recent measures by St. John. Since wave-lengths at the edge of the sun are free from the effect of radial currents, their displacement at the edge of the sun in

TABLE XV

RED DISPLACEMENT OF THE CYANOGEN LINES IN THE 3883-BAND

(Unit for $\Delta\lambda = 0.001$ A)

Region	No. of Lines	$\Delta\lambda$	Region	No. of Lines	$\Delta\lambda$
λ 3729–λ 3782....	103	+3.8	λ 3793–λ 3819...	49	+4.4
3782– 3810....	103	4.2	3819– 3850...	46	4.3
3810– 3843....	103	5.1	3850– 3866...	45	5.5
3843– 3865....	103	4.6	3866– 3881...	44	+5.7
3865– 3883....	103	+4.9			
Mean for 515 lines (center)		+4.6	Mean for 184 lines (center)		+5.0
Mean for 515 lines (limb)..		7.2	Mean for 184 lines (limb)..		7.6
Relativity shift..........		+8.1	Relativity shift..........		+8.1

reference to arc wave-lengths furnishes an appropriate measure of the red shift of Fraunhofer lines. For the *CN* lines the displacement at the limb is of the sign and approximate magnitude required by the theory of relativity.

CONCLUSION

Lines originating at a level of 520 km above the sun's photosphere show displacements at the center of the sun in agreement with those given by general relativity (Table X).

Below this level, in the region where 99 per cent of solar lines originate, upward currents exist in the sun's atmosphere, which increase in strength with nearness to the photosphere. The iron lines of lowest level give a velocity of approximately 0.22 km/sec. upward; the effect vanishes at the edge of the sun so that for these lines the difference, λ at edge of sun *minus* λ for arc in vacuum, is the

predicted Einstein displacement. When the high-, medium-, and low-level lines of iron are considered, the mean residual, λ at edge of sun *minus* λ for arc in vacuum, differs from Einstein's prediction by $+0.0015$ A. This difference, if real, is a true limb effect.

This investigation confirms by its greater wealth of material and in greater detail the conclusion announced in the Symposium on Eclipses and Relativity at Los Angeles, September 17, 1923, that the causes of the differences at the center of the sun between solar and terrestrial wave-lengths are the slowing up of the atomic clock in the sun according to Einstein's theory of general relativity, and radial velocities of moderate cosmic magnitude and in probable directions, or equivalent conditions whose effects vanish at the edge of the sun.

My thanks are due to Mr. Babcock for checking the grating measures by the interferometer, to Miss L. M. Ware, Mrs. W. S. Adams (née Miller), and Mr. E. F. Adams for assistance in the measurements, reductions, and compilation, and to Miss Charlotte E. Moore for excitation potentials. To Professor W. W. Campbell and Professor W. H. Wright, for copies of their remarkable eclipse and nebular spectra, and to Professor Z. A. Merfield, for unpublished material, I wish to express my grateful appreciation.

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THE EFFECT OF PRESSURE ON THE SPECTRUM OF THE IRON ARC[1]

By HAROLD D. BABCOCK

ABSTRACT

Pressure effect in the arc spectrum of iron, λ 3895–λ 6678, *for pressures below 1 atmosphere.*—For 130 spectral lines (Table II) observed in arcs considered to be free from pole effect, displacements due to change of pressure are accurately measured with Fabry-Perot interferometers. With the aid of a list of terms and their combinations, the displacements are interpreted as the result of depressions of the terms with increase of pressure (Table III), high-level terms being much more affected than those of low level, and those of quintet and septet multiplicity more than the triplet terms. Empirical expressions of these relations are developed, which make it possible to predict the pressure effect for both terms and lines. No connection is found between term displacements and azimuthal or inner-quantum numbers.

Discussion of results by Gale and Adams for Fe and Ti.—The observed line displacements (Table II) are systematically less than those of other observers, but full qualitative agreement is found between the new data and those of Gale and Adams. Their classification of lines according to pressure groups is thus given numerical significance and is shown to have a definite physical basis.

Theories which attribute pressure effect to coupling forces between adjacent similar atoms are found to be inconsistent with the data.

Numerical definition of temperature classification.—Statistical examination of the levels for each temperature class assigned by King in the spectra of *Fe, Ti, Sc,* and *Ba* shows that in general a progression of one temperature class corresponds to a change of about 0.70 volt in the level of the terms involved. The coefficient for *Ca* is 0.35 volt.

I. INTRODUCTION

The discovery of the pressure effect by Humphreys and Mohler[2] revealed a phenomenon whose nature is still imperfectly understood. The well-known effects of temperature and of electric and magnetic fields have proved powerful aids in the development of the modern theory of spectra and have found satisfactory explanation therein. The effect of pressure, on the other hand, has contributed nothing to the growth of the quantum theory, and in recent treatises has indeed scarcely been mentioned. For example, Sommerfeld's *Atombau und Spektrallinien* devotes many pages to the Zeeman effect and the Stark effect, but makes no reference to the pressure effect.

Following the work of Humphreys and Mohler, a number of observers contributed important measurements of the changes produced in arc, spark, and furnace spectra by increase of pressure on

[1] *Contributions from the Mount Wilson Observatory,* No. 350.

[2] *Astrophysical Journal,* **3**, 114, 1896.

the source of light. Thus Humphreys,[1] Hale and Kent,[2] Anderson,[3] Duffield,[4] Rossi,[5] Gale and Adams,[6] and King[7] examined the spectra of many elements, chiefly at high pressures, while Fabry and Buisson[8] measured the displacements of a few lines produced by reducing the pressure from 1 atmosphere to a vacuum.

During the last fifteen years little of importance has been added to our knowledge of this subject. It would seem either that the existing data are confused by some effect other than that of pressure alone, or that their relation to the features of atomic structure at present accepted is indeed obscure. No attempt to interpret the effect in terms of the quantum theory appears to have been made.

The discovery of pole effect by Goos,[9] and further study of it by other observers, have proved helpful, however, in the comparison of observations of pressure effect; and, as illustrated below, some discrepancies may be explained by its unsuspected presence in the sources of light. The pressure displacements for certain groups of lines were thus changed by amounts dependent on the conditions under which the light was produced in each case.

This paper, following a preliminary note,[10] describes some new observations of the pressure effect, made under conditions designed to eliminate as far as possible other causes of displacement of the spectral lines, either real or instrumental. From combinations of the observed effects for spectral lines, the behavior of many of the spectral terms under variation of pressure is found and examined in relation to energy level, multiplicity, and quantum number. The measurements of Gale and Adams are thus studied, and, except for a

[1] *Ibid.*, **4**, 249, 1896; **6**, 169, 1897; **22**, 217, 1905; **26**, 18, 1907.

[2] *Ibid.*, **17**, 154, 1903.

[3] *Ibid.*, **24**, 221, 1906.

[4] *Ibid.*, **26**, 375, 1907; *Philosophical Transactions of the Royal Society*, A, **208**, 11, 1908.

[5] *Proceedings of the Royal Society*, A, **83**, 414, 1910.

[6] *Mt. Wilson Contr.*, No. 58; *Astrophysical Journal*, **35**, 10, 1912.

[7] *Mt. Wilson Contr.*, No. 60; *Astrophysical Journal*, **35**, 183, 1912.

[8] *Ibid.*, **31**, 112, 1910.

[9] *Ibid.*, **38**, 141, 1913.

[10] Read at the Reno meeting of the American Physical Society, June, 1927; *Physical Review*, Ser. 2, **30**, 366, 1927.

systematic difference in the amount of the displacement, are found to be in general agreement with the new results.

In addition, the temperature classification of spectral lines, studied extensively by King, is given a new quantitative description which extends still further its usefulness.

2. METHODS AND APPARATUS

Former measurements of the effect of pressure have nearly all been made by comparing spectra at atmospheric pressure and at much higher pressures, even up to 100 atmospheres. In the present work, however, the comparison was made between an open arc and one in a vacuum chamber; and since the average height of the barometer in Pasadena is about 74.5 cm, all pressures were below 1 standard atmosphere. The reason for choosing this restricted range of pressure was to reduce the errors of measurement inevitably connected with the comparison of two very dissimilar images of a spectral line, and also to avoid the disturbing influence of pole effect, which becomes troublesome at pressures above 1 atmosphere. For example, it was shown by St. John and Babcock[1] that pole effect may be a potent source of difficulty in observations of the pressure effect, and further illustration will be offered below. Furthermore, St. John and Babcock found no pole effect in a vacuum arc, and in a subsequent paper[2] they showed that an open arc of the Pfund type, operated at a length of 15 mm with a current of 5 amperes or less, has a narrow central zone, perpendicular to the axis of the arc, which is free from pole effect.

In the present work particular attention has been given to the operation of the arc, and the only deviations from the conditions mentioned above have been in the use of a still longer arc and of a lower current strength, thus tending to reduce still further any possible disturbance from pole effect. It may be recalled that in the Pfund arc the anode is below and that it consists of a bead of the metal whose spectrum is desired, resting in the hollowed upper end of a massive rod of iron or copper. The metal bead must be completely oxidized before the arc is used for observation. The cathode

[1] *Mt. Wilson Contr.*, No. 106; *Astrophysical Journal*, **42**, 1, 1915.

[2] *Mt. Wilson Contr.*, No. 137; *Astrophysical Journal*, **46**, 231, 1917.

is a rod of steel 6 or 7 mm in diameter, with a heavy cylinder of brass fitted near the lower end, which permits only 2 or 3 mm of steel to protrude. The vacuum arc was of the same type. The pressure was controlled by stop-cocks in the pump connection, and was read on a mercury manometer. No gases other than air have been used thus far.

The spectra were all obtained by means of Fabry-Perot interferometers used with a concave grating for auxiliary dispersion, as described in previous papers. On account of the reduced range of pressures employed, greater refinement is required in the spectroscopic measurements than has hitherto been attempted in the study of the pressure effect. For this purpose the Fabry-Perot interferometer is exceptionally well adapted, surpassing all other instruments except the Lummer-Gehrcke plate, and in some respects is superior to that.

The measurements of the small displacements produced by a change of pressure amounting to 1 atmosphere or less were carried out in two series. For the first a strictly differential method was used, while for the second the actual wave-lengths of the lines at the two pressures were determined. The differential method has the advantage of requiring no corrections, while in the second method these must be applied. After describing some details of the two series of measurements, the close agreement in the results will be shown, and the combined data will then be examined with the aid of the quantum theory in an attempt to trace some connection between the structure of the atom and the influence of pressure.

In both methods interferometers of several thicknesses have been used, chiefly of medium thickness with orders of interference of 25,000–50,000. The apertures of the optical projecting systems were so chosen as to provide from fifteen to forty images of interference rings on each spectral line. In the differential method two such photographs were made in succession, one at atmospheric pressure and one at reduced pressure, and the diameter of each interference ring on the first photograph was compared with that of the homologous ring on the second. Each pair of plates therefore provides a considerable number of determinations of the displacement which each spectral line has undergone as a result of changing the pressure.

The change of wave-length, $\Delta\lambda$, is a function of the product of the linear diameter, D, and its variation, ΔD, and is given by

$$\Delta\lambda = \frac{\lambda}{4F^2m^2} D\Delta D ,$$

where F is the focal length of the projector which forms on the slit the image of the interference pattern and m is the magnification of the spectrograph for the wave-length, λ. The factor $4F^2m^2$ is easily found from the diameters of the rings with greater precision than is necessary for the present purpose. Since m is constant over a range of about 1000 A on each photograph, the determination of the coefficient of $D\Delta D$ cannot introduce any appreciable error into the results. No measurements are required except those of the diameters of the rings.

Since the two photographs required by the differential method cannot be made simultaneously, there is always a possibility of minute variation occurring in the etalon, and the quantity sought is so small that it becomes necessary to make allowance for any such change. Accordingly, the spectral lines of some constant source, such as a vacuum mercury arc or a neon lamp, are impressed on every plate simultaneously with the spectrum of iron. Measurements of these lines, whose wave-lengths remain the same, show the amount of any change in the etalon. If D' and $\Delta D'$ refer to a reference line, we have

$$\Delta\lambda = \frac{\lambda}{4F^2m^2}(D\Delta D - D'\Delta D') .$$

The variation in the etalon was usually equivalent to only a few ten-thousandths of an angstrom.

Displacements corresponding to a change of 1 atmosphere were measured by this method for seventy lines. Tests on a few selected lines for intermediate changes of pressure, e.g., 40 cm of mercury, showed effects proportional to the change of pressure, at least within the errors of observation. This is in agreement with the proportionality noted by other observers for pressures above 1 atmosphere.

In the second method the spectrum of neon was photographed

simultaneously with each exposure to iron, and the wave-lengths of the iron lines were determined in the usual manner in terms of the neon standards, both at 1 atmosphere and at reduced pressure. Details of the procedure have been described in previous papers. This method has been used for wave-lengths greater than λ 4900, while the first method was employed mainly in the region of shorter wave-lengths.

A comparison between the two series of measurements is shown in Table I, which gives mean values of the displacements for lists of common lines. The last column contains the average displacements

TABLE I

COMPARISON OF THE TWO SERIES OF OBSERVATIONS WITH EACH OTHER AND WITH RESULTS OF GALE AND ADAMS

Group	No. Lines	Mean	$\Delta\lambda$ per Atmosphere		
			Series		Gale and Adams
			I	II	
a	19	5266 A	+0.0019 A	+0.0020 A	+0.0035 A
b	17	6335	.0030	.0030	.0090
d	15	5198	.0056	.0062	.012
d	9	5625	+0.0063	+0.0064	+0.017

per atmosphere observed by Gale and Adams for some of the same lines. It seems probable that most of the difference between their results and mine is to be explained by the presence of pole effect in their sources of light.

It is evident that the new results are significant in the fourth decimal place and that the two series may be combined with considerable confidence in their accuracy. Measurements such as these, made on a few selected iron lines, would suffice to determine the pressure within 3 or 4 cm of mercury.

3. OBSERVATIONAL RESULTS

Table II gives the combined results of the two series for all the iron lines which have been measured. As implied above, some of the lines have been observed by only one method. The first column gives the wave-length of the lines in the open arc, the second shows the

displacements expressed on the scale of wave numbers, since it is on this scale that they must later be examined. The group to which the line has been assigned is found in the third column, with occasional changes from the earlier classification. Except in the case of a few lines not yet identified, the last column shows the multiplet designation of the line, the notation being that of Russell.[1]

4. DISCUSSION

Attention is directed to the fact that the observed line displacements, with increase of pressure, are always toward longer wavelengths, even for lines of group *e*, which have hitherto been in doubt. This fact may be taken as indication of the freedom of the observations from pole effect, for in the case of lines of group *e* the displacement due to pole effect is toward the violet.

Thirty-nine multiplets are represented in the last column of Table II, although for some of them the displacement of only one line has been measured as yet. Inspection shows at once that the members of a multiplet behave alike under change of pressure, which indicates that the terms on which the lines depend are influenced by the pressure. The mean displacement was accordingly taken for each multiplet, and this revealed the fact that the larger displacements are associated with multiplets whose upper terms are among the highest in the atom—a relation already shown by the classification of Gale and Adams which will be discussed below.

The increase of wave-length, or decrease of wave-number, which is here found always associated with increase of pressure on the source, may be thought of as arising from changes in the energy level which affect by different amounts the two terms involved in the production of the line. To account for the observations two alternatives are presented, namely, the depression or the elevation of the terms by increase of pressure. Although arithmetically equivalent, these hypotheses are physically very different, since elevation of the terms would require that those of low level should be most affected, while depression would mean that high-level terms should be most sensitive. Abundant evidence leads to the choice of the depression hypothesis, with high levels more affected than those that are lower.

[1] *Mt. Wilson Contr.*, No. 345; *Astrophysical Journal*, **66**, 347, 1927.

TABLE II

PRESSURE DISPLACEMENTS PER ATMOSPHERE FOR IRON LINES

λ at 1 Atm.	$\Delta\nu$ 10^3 cm^{-1}	Pressure Group	Multiplet	λ at 1 Atm.	$\Delta\nu$ 10^3 cm^{-1}	Pressure Group	Multiplet
3895.658....	6	*a*	a^5D-a^5D'	5074.757....	27	*e*	b^5F-x^3G
3899.708....	6	*a*	a^5D-a^5D'	5083.342....	8	*a*	$a^5F'-a^5F$
3902.948....	14	*b*	$a^3F'-b^3D'$	5133.692....	8	*e*	b^5F-uy
3906.481....	13	*a*	a^5D-a^5D'	5162.288....	54	*d*	....
3920.259....	6	*a*	a^5D-a^5D'	5167.490....	5	*a*	$a^3F'-a^3D'$
3922.913....	10	*a*	a^5D-a^5D'	5171.599....	7	*a*	$a^3F'-a^3F$
3927.921....	6	*a*	a^5D-a^5D'	5192.350....	21	*d*	a^7P-x^7D
3930.298....	6	*a*	a^5D-a^5D'	5208.601....	22	*d*	$a^5D'-x^5D$
3969.260....	14	*b*	$a^3F'-b^3F$	5227.191....	6	*a*	$a^3F'-a^3D'$
4005.244....	19	*b*	$a^3F'-b^3F$	5232.946....	21	*d*	a^7P-x^7D
4045.814....	12	*b*	$a^3F'-b^3F$	5242.495....	11	*a*	....
4063.597....	12	*b*	$a^3F'-b^3F$	5250.650....	7	*a*	$a^5P'-b^5P$
4071.741....	13	*b*	$a^3F'-b^3F$	5263.314....	23	*d*	$a^5D'-x^5D$
4084.499....	20	*d*	a^5F-y^5D	5266.562....	20	*d*	a^7P-x^7D
4153.905....	33	*d*	....	5269.541....	11	*a*	$a^5F'-a^5D'$
4181.758....	11	*b*	....	5270.359....	4	*a*	$a^3F'-a^3D'$
4187.044....	25	*d*	$a^7D'-x^7D$	5281.796....	18	*d*	a^7P-x^7D
4187.802....	23	*d*	$a^7D'-x^7D$	5283.628....	23	*d*	$a^5D'-x^5D$
4191.436....	23	*d*	$a^7D'-x^7D$	5302.307....	26	*d*	$a^5D'-x^5D$
4198.310....	23	*d*	$a^7D'-x^7D$	5324.185....	22	*d*	$a^5D'-x^5D$
4199.098....	12	*b*	....	5339.936....	22	*d*	$a^5D'-x^5D$
4202.032....	12	*b*	$a^3F'-a^3G'$	5341.025....	4	*a*	$a^3F'-a^3D'$
4210.352....	26	*d*	$a^7D'-x^7D$	5364.874....	6	*e*	$a^5G'-wy$
4227.434....	36	*d*	....	5367.470....	6	*e*	$a^5G'-y^5F'$
4233.608....	28	*d*	$a^7D'-x^7D$	5369.965....	9	*e*	$a^5G'-y^5F'$
4235.942....	25	*d*	$a^7D'-x^7D$	5371.493....	9	*a*	$a^5F'-a^5D'$
4250.125....	24	*d*	$a^7D'-x^7D$	5383.374....	13	*e*	$a^5G'-vy$
4250.790....	13	*b*	$a^3F'-a^3G'$	5393.174....	17	*d*	$a^5D'-x^5D$
4260.480....	22	*d*	$a^7D'-x^7D$	5397.130....	9	*a*	$a^5F'-a^5D'$
4271.159....	24	*d*	$a^7D'-x^7D$	5400.509....	27	*e*	$a^5G'-yy$
4271.764....	14	*b*	$a^3F'-a^3G'$	5404.143....	6	*e*	$a^5G'-y^5F'$
4282.406....	7	*a*	$a^5P'-a^5S'$	5405.777....	6	*a*	$a^5F'-a^5D'$
4294.128....	10	*b*	$a^3F'-a^5G'$	5410.913....	7	*e*	....
4299.242....	23	*d*	$a^7D'-x^7D$	5415.201....	7	*e*	$a^5G'-y^5F'$
4315.087....	6	*a*	$a^5P'-a^5S'$	5424.072....	10	*e*	$a^5G'-y^5F'$
4375.932....	6	*a*	a^5D-a^7F	5429.699....	7	*a*	$a^5F'-a^5D'$
4494.567....	18	*c*	$a^5P'-c^5D'$	5434.526....	7	*a*	$a^5F'-a^5D'$
4528.618....	17	*c*	$a^5P'-c^5D'$	5445.045....	7	*e*	$a^5G'-xy$
4859.747....	19	*d*	a^7F-x^7D	5446.919....	8	*a*	$a^5F'-a^5D'$
4878.217....	19	*d*	a^7F-x^7D	5455.613....	7	*a*	$a^5F'-a^5D'$
4891.496....	26	*d*	a^7F-x^7D	5497.518....	4	*a*	$a^5F'-a^5D'$
4918.999....	17	*d*	a^7F-x^7D	5501.468....	6	*a*	$a^5F'-a^5D'$
4920.509....	25	*d*	a^7F-x^7D	5506.782....	8	*a*	$a^5F'-a^5D'$
4966.094....	24	*d*	a^5F-x^5F'	5569.624....	22	*d*	a^5F-x^5D
4994.133....	8	*a*	$a^5F'-a^5F$	5572.848....	21	*d*	a^5F-x^5D
5001.871....	20	*d*	a^3F-x^3D	5576.095....	13	*d*	a^5F-x^5D
5012.071....	7	*a*	$a^5F'-a^5F$	5586.762....	19	*d*	a^5F-x^5D
5014.950....	28	*d*	a^2F-x^3D	5615.650....	20	*d*	a^5F-x^5D
5022.245....	32	*d*	a^3F-x^3D	5624.549....	21	*d*	a^5F-x^5D
5049.824....	13	*b*	$a^3P'-b^3D'$	5658.824....	22	*d*	a^5F-x^5D
5051.637....	11	*a*	$a^5F'-a^5F$	5662.522....	16	*d*	b^5F-y^5D
5068.774....	29	*d*	a^7P-x^7D	5709.386....	25	*d*	a^5F-x^5D

TABLE II—*Continued*

λ at 1 Atm.	$\Delta\nu$ 10^3 cm^{-1}	Pressure Group	Multiplet	λ at 1 Atm.	$\Delta\nu$ 10^3 cm^{-1}	Pressure Group	Multiplet
5753.134....	33	*d*	a^3P-x^3D	6335.335....	12	*b*	$a^5P'-b^5D'$
6024.066....	22	*e*	b^3F-y^5F'	6336.830....	17	*d*	a^5P-x^5D
6065.486....	8	*b*	$b^3F'-b^3F$	6393.605....	10	*b*	$a^3H'-a^5G'$
6136.618....	6	*b*	$a^3H'-a^3G'$	6400.010....	22	*d*	a^5P-x^5D
6137.696....	14	*b*	$b^3F'-b^3F$	6408.025....	18	*d*	a^5P-x^5D
6191.562....	10	*b*	$a^3H'-a^3G'$	6411.653....	10	*d*	a^5P-x^5D
6219.284....	3	*b*	$a^5P'-b^5D'$	6421.355....	12	*b*	$a^3P'-a^3P$
6230.728....	13	*b*	$b^3F'-b^3F'$	6430.851....	10	*b*	$a^5P'-b^5D'$
6246.327....	23	*d*	a^5P-x^5D	6494.985....	10	*b*	$a^3H'-a^5G'$
6252.560....	10	*b*	$a^3H'-a^3G'$	6546.244....	7	*b*	a^3G-b^3F
6254.261....	10	*b*	$a^3P'-a^3P$	6569.227....	28	*d*	....
6301.505....	13	*d*	a^5P-x^5D	6592.919....	12	*b*	a^3G-b^3F
6318.022....	12	*b*	$a^3H'-a^5G'$	6677.993....	7	*b*	a^3G-b^3F

To adopt the other view would be inconsistent with all the mechanics of the atom.

It was therefore assumed that the depression of the lowest term in the iron atom, a^5D, is zero, and, in order to derive the effects on the separate terms, the mean values of $\Delta\nu$ for the multiplets were then combined by adding or subtracting those for multiplets having one term in common. For example, from Table II, the average $\Delta\nu$ for the multiplet a^5D-a^5D' is found to be 0.0076 cm^{-1}, while for the multiplet $a^5D'-x^5D$ it is 0.0236 cm^{-1}. It follows that the depression of the term a^5D' is on the average 0.0076 cm^{-1}, and of the term x^5D, 0.0312 cm^{-1}.

The depressions of the individual terms found by this method from the data of Table II are listed in Table III, in which the terms are arranged according to multiplicity and energy level. Lack of observations on certain lines which would connect all the terms directly with a^5D necessitated two additional assumptions, namely, that the depression of a^3F' is 0.001 cm^{-1}, and of a^5P', 0.003 cm^{-1}. On account of the extremely low levels of these terms there can be little doubt of the correctness of the assumptions, and in fact the results themselves serve as an excellent check on the validity of the proceeding.

Table III is shown graphically in Figure 1, where the energy levels of the terms are plotted as abscissae and their depressions as ordinates. The multiplicity of each term is indicated, but for the

weight of each observation reference must be made to the table. The figure shows that terms of septet and quintet multiplicity are affected somewhat more than the triplet terms, and that for each multiplicity the effect increases from terms of low level to those of high level.

TABLE III

DEPRESSION OF IRON TERMS DUE TO CHANGE OF PRESSURE FROM 0 TO 1 ATMOSPHERE

TERM	TRIPLETS		WT.	TERM	QUINTETS AND SEPTETS		WT.
	Mean Level	Depression			Mean Level	Depression	
	cm^{-1}	cm^{-1}			cm^{-1}	cm^{-1}	
a^3F'	12,500	0.001	......	a^5D	0	0.000	......
a^3P'	18,700	.002	1	a^5F'	7500	.000	3
a^3H'	19,600	.003	3	a^5P'	17,700	.003	......
b^3F'	20,800	.003	3	a^7D'	19,600	.003	3
a^3G	22,000	.007	3	a^7F	23,000	.006	1
a^3D'	31,600	.006	3	a^7P	24,100	.005	3
a^3F	31,700	.008	1	a^5D'	26,200	.008	3
a^3P	34,200	.013	2	a^5F	27,300	.009	3
a^3G'	35,700	.014	3	a^5P	29,400	.012	3
b^3F	37,100	.015	3	b^5D'	33,600	.015	3
b^3D'	38,600	.015	1	b^5F	34,200	.013	1
x^3D	51,600	.035	3	a^5G'	35,400	.011	1
x^3G	54,000	0.040	1	b^5P	37,100	.007	1
				c^5D'	40,000	.020	2
				a^5S'	40,900	.010	1
				x^7D	43,300	.027	3
				x^5D	45,200	.029	3
				x^5F'	47,600	.033	1
				y^5D	51,800	.029	1
				Undetermined	53,800	.038	1
				y^5F'	53,900	0.028	1

An examination of the data in Table III has been made by the method of least squares, on the basis of a relation of the form

$$d=AV+BV^2\,,$$

where d and V represent the depression of a term and its level, respectively, and A and B are constants to be determined. It was found that for V expressed in volts and d in units of 0.001 cm^{-1}, the data for triplet terms may be expressed by the equation

$$d=1.15V^2-1.93V\,.$$

Since no distinction appears in the behavior of septets and

quintets, they were discussed as one group. From all the observations of these terms it was found that

$$d=0.94V^2-0.61V\ .$$

Figure 1 shows, however, that five quintets of lowest weight fall systematically below the terms of high weight, deviating much more widely than the others do among themselves. If these five are omitted, the relation for the remaining quintets and septets becomes

$$d=1.15V^2-1.27V\ .$$

The curves of Figure 1 represent this equation and the corresponding formula for the triplet terms. There seems little doubt that the

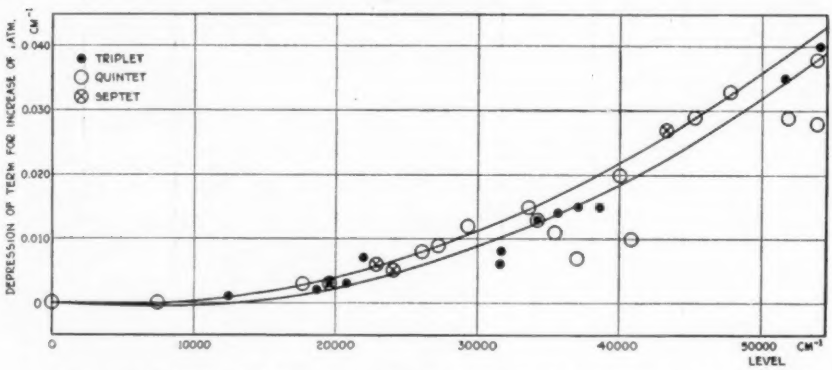

FIG. 1.—Relation between pressure effect on spectral terms of iron and their level in the atom.

effect of pressure is greater for the higher multiplicities. No relation has been found between the sensitivity of a term to pressure and the azimuthal quantum number associated with it.

It may be remarked that the percentage displacement which a spectral line undergoes, $\Delta\nu/\nu$ or $\Delta\lambda/\lambda$, is given by the slope, on a diagram like Figure 1, of the line joining the two terms involved. This quantity is obviously greatest for lines of long wave-length arising from a transition between terms of highest level. On the other hand, the greatest physical effect, $\Delta\nu$, is found for lines of shortest wave-length, since these are produced by transitions between terms of highest and of lowest levels, for which the difference in depression is greatest.

The displacements of the lines listed in Table II were examined for possible correlation between magnitude of displacement and inner-quantum number of the upper term, but no definite relation was found. If such a relation exists, the combination rules for inner-quantum numbers might be expected to conceal the effect except for multiplets involving one very high level and one quite low. Extremely accurate measurements in the ultra-violet would afford an interesting test of the question. It might be objected that the intensities of the lines in a multiplet vary with the inner-quantum numbers and could thus introduce spurious effects. The observed intermingling of consistent large and small displacements for different multiplets on the same photograph argues against such an intensity effect, and this is supported by a comparison of Table II with the intensities of the lines as estimated by other observers. Adjacent lines of the same intensity belonging to different multiplets show displacements in the ratio of 2 or more to 1. Furthermore, the range of intensities within a given multiplet is often considerable, yet the displacements generally agree within the errors of measurement.

It is evident that the pressure effect for a line which has been placed in a multiplet may be read from the curves of Figure 1, which display the relation between the level of a term and the depression which it experiences when the pressure is increased from 0 to 1 atmosphere. For example, with the weak excitation which is necessary in the arcs in order to avoid pole effect, the infra-red region is difficult to observe with high resolving power as in the methods used here. But some of the important terms which have combinations occurring in that region have been observed by means of other combinations which produce lines easily accessible; and, furthermore, the preceding equations which express the relation between the level of a term and its pressure effect permit the calculation of the effect for terms not included in Table III as well as the improvement of those which are listed there. An illustration is found in the multiplet b^5F-x^5D in the region of 9100 A. The difference in the depressions of these two terms is 0.014 cm^{-1}, or 0.0116 A, which is the amount of true pressure displacement to be expected for these lines. For a large number of iron lines astrophysically most important, the wave-lengths now available from the arc at atmospheric

pressure are highly reliable. In the region λ 2373–λ 8824 approximately one thousand lines, including many of these, have been identified in multiplets, and for such lines the wave-lengths which would have been found if the arc had been *in vacuo* can easily be derived. The accuracy of the results obtained in this way is essentially the same as that for wave-lengths determined from the arc at 1 atmosphere.

Conversely, observations of the displacement due to variation of pressure may lead to the discovery of new terms or of new combinations of known terms. Although these desirable things have not yet been accomplished with the data of Table II, attention may be directed to a few lines for which the observations are particularly interesting and for which the terms have not yet been identified. Most conspicuous are the three lines λλ 4153.905, 4227.434, and 5162.288, all of which show exceptionally large displacements, which do not fit even on the steepest part of the curve for quintet and septet terms given in Figure 1. The observations on λ 4153 and λ 4227 might be explained by postulating the existence of a septet or quintet term of level about 55,000 cm^{-1} capable of combining with a^3D' or a^3F; but λ 5162 cannot be accounted for in this way, and it appears more plausible to suggest the existence of terms of fairly high level having ninefold multiplicity.

Among other unidentified iron lines in Table II, only two will be mentioned—λλ 4181.758 and 4199.098. Since they have the same pressure effect, it seems probable that they belong in the same multiplet. Being of group *b*, they are probably produced by a combination involving one or more triplet terms, and the observed values of $\Delta\nu$ and ν, when compared with Figure 1, indicate the location of the terms. Systematic search for such terms has not yet been made with the aid of the data given here. The present purpose is to indicate the usefulness of the new results.

5. COMPARISON WITH OTHER OBSERVATIONS

In general, the line displacements communicated in this paper are less than those found by other observers. As an example, the results obtained by Fabry and Buisson[1] from a comparison of the

[1] *Astrophysical Journal*, **31**, 112, 1910.

vacuum iron arc with an open arc are listed in Table IV along with the corresponding displacements from Table II, expressed here on the scale of wave-lengths. The last two columns of Table IV give the difference, Fabry and Buisson *minus* Babcock, and the amount of the displacement due to pole effect as observed by St. John and Babcock[1] for the same iron lines. The correlation between these two columns is a clear indication that the open arc used by Fabry and Buisson exhibited much pole effect, and that this contributed more to their observed displacements than did the change of pressure. It

TABLE IV

POLE EFFECT IN SOME MEASUREMENTS OF PRESSURE EFFECT

Pressure Group	λ	Pressure Effect		Difference	Pole Effect
		Fabry and Buisson	Babcock		
		A	A	A	A
a............	4315	+0.004	+0.0012	+0.0028	0.000
	5434	+ .001	.0021	− .0011	.000
b............	4181	+ .002	.0020	.0000	.000
d............	4187	+ .011	.0043	+ .0067	+ .008
	4191	+ .010	.0040	+ .0060	+ .010
	4227	+ .020	.0064	+ .0136	+ .014
	4233	+ .012	.0050	+ .0070	+ .010
	4236	+ .011	.0044	+ .0066	+ .009
	4250	+ .013	.0044	+ .0086	+ .010
	4860	+ .017	.0044	+ .0126	+ .014
e............	5415	− .015	.0025	− .0175	− .025
	5424	−0.017	+0.0030	−0.0200	−0.026

has already been shown (Table I) that the measurements of Gale and Adams gave results in excess of mine by amounts of the same order of magnitude as the differences shown in Table IV.

The question arises: May there not still be a remnant of pole effect in my arc which is responsible for the displacements? Table IV shows a correspondence between my determination of the pressure displacement and the observed pole effect for the lines of group *d*. But the apparent relation disappears in the case of lines of groups *a* and *b*, and is actually reversed for the sensitive lines of group *e*, which provide a convincing negative answer to the question. The two examples of group *e* listed in Table IV are confirmed by eleven

[1] *Mt. Wilson Contr.*, No. 106; *Astrophysical Journal*, **42**, 1, 1915.

others in Table II, definitely establishing the fact that increase of pressure normally displaces all classes of iron lines toward the red. A clear distinction is thus drawn between pole effect and pressure effect.

Observations of the Stark effect for iron are not numerous, but in so far as it is possible to compare them with those of pole effect, a general correspondence is found. Lines widened unsymmetrically by the electric field are widened and displaced in the same direction by pole effect. It may be that pole effect is nothing but the evidence of inter-atomic electrical fields.

It will be interesting to examine now in more detail some of the former measurements of the pressure effect, and for this purpose we turn to the important paper of Gale and Adams already mentioned.

With the aid of the list of terms in the iron spectrum and their known combinations, the levels have been tabulated for the lines classified by Gale and Adams into the groups *a*, *b*, *c*, and *d*, respectively. Their original list of classified iron lines has been extended in recent years by several methods. The results are consistent with the original classification, although little distinction is now found between *c* and *d*, while a fifth group, *e*, has been added by St. John and Miss Ware.[1]

The tabulated system of levels associated with each group, as noted above, was first examined with respect only to the term of higher level in each transition. Table V gives the limits within which are included the upper terms of each group. Most of the lines formerly classed in group *c* have here been included in *d*. Two peculiarities at once attract attention: There are no gaps between the respective intervals of level, and, except for the small group *e*, there is no overlapping of the intervals. Similar treatment of the lower terms shows that in all three groups, *a*, *b*, and *d*, the intervals overlap almost completely.

It is clear that the upper term in the transition determines the group to which a line belongs, and that the terms of highest level are associated with the lines most sensitive to pressure.

Another feature of the classification of Gale and Adams requires attention, namely, the class numbers which they assign to designate

[1] *Mt. Wilson Contr.*, No. 75; *Astrophysical Journal*, **38**, 209, 1913.

the appearance of lines under pressure, irrespective of the amount of displacement. Unfortunately this feature of their classification has not been extended as in the case of the groups, and the material available for examination is comparatively small. Nevertheless, if the lower terms involved in the transitions corresponding to each class number are listed together, a definite relation is observed. For classes 1 and 3 the mean level of the lower terms is 5000 cm^{-1}, for class 4 the mean is 18,000 cm^{-1}, and for class 5 it is 26,000 cm^{-1}. Examination of class 3 lines shows that in general these are weaker lines in the same multiplets as those involved in class 1. Because of their diminished intensity they naturally show less evidence of self-reversal and have been classified separately; but it is clear that classes

TABLE V

NUMERICAL DEFINITION OF GALE AND ADAMS' GROUPS OF IRON LINES

Group	Limits of Upper Terms
a	19,700–32,500 cm^{-1}
b	32,500–41,500
d	41,500–55,000
e	53,500–55,000

1 and 3 belong together, since their only difference is one of degree. The increasing level of the lower term with increasing class number, and hence with decreasing reversibility, is quite in keeping with the relative numbers of atoms in the various states of excitation at any instant as deduced from the theory of ionization and as observed in studies of the temperature effect on spectra. The upper levels, on the other hand, show little relation to the class numbers, about half of those associated with class 4 being the same as those of class 1.

Turning now to the measurements of Gale and Adams for titanium, we find that they used both arc and spark. The average displacement was somewhat greater for the spark, but the poorer quality of the lines introduced larger errors. It will be sufficient for our purpose to consider only the results which they obtained from the arc.

Inspection shows that the members of a multiplet behave alike,

especially in the case of the lines best suited to measurement. The average was accordingly taken for each multiplet and reduced to what it would have been had the change of pressure been 1 atmosphere instead of 8, and, finally, to the scale of wave-numbers. Depressions of the titanium terms were then derived from combinations of the data for the multiplets, by the method applied to my observations of the iron spectrum, and on the assumption that the lowest term in titanium is unaffected by pressure. The pressure effects thus

TABLE VI

PRESSURE EFFECT FOR TITANIUM TERMS DERIVED FROM THE MEASUREMENTS OF GALE AND ADAMS

Term	Level	Depression	Weight	Term	Level	Depression	Weight
	Volts	cm^{-1}			Volts	cm^{-1}	
a^3F'	0.00	0.000	......	b^5G'	3.29	0.025	3
a^5F'	0.82	.011	1	c^3F	3.30	.009	2
a^3P'	1.05	.006	2	c^3D'	3.39	.019	1
b^3F'	1.44	.008	3	b^3G'	3.41	.028	2
a^5D'	2.28	.010	2	b^5F	3.55	.029	3
a^3F	2.38	.009	3	d^3D'	3.68	.027	3
a^3D'	2.46	.007	2	c^3G'	3.70	.027	1
a^3G'	2.64	.010	1	c^5D'	3.70	.026	3
a D′	2.72	.005	1	e^3D'	3.85	.023	1
a G′	3.01	.010	1	d^3G'	3.89	.030	1
a^3S'	3.08	.012	1	c^3P	4.09	.015	2
b^3F	3.11	.010	3	e^3F	4.21	0.033	1
b^3D'	3.13	0.010	2				

found for twenty-five terms are listed in Table VI, together with the levels of the terms and numbers indicating the weights to be attached to the results. The notation and the levels are from a paper by Russell.[1] The weights are dependent on the numbers of lines involved in each multiplet, but no attempt has been made to take account of the deviations in the measured values of the pressure displacement.

Table VI, however, takes no account of thirteen titanium lines for which Gale and Adams found very large displacements. The behavior of the upper terms involved in these lines is inconsistent with that of other terms of the same level and is not readily explained. The lines are all greatly widened unsymmetrically, and are unre-

[1] *Mt. Wilson Contr.*, No. 345; *Astrophysical Journal*, **66**, 347, 1927.

versed, so that possibly the true effect of pressure is in this case combined with some other agency like pole effect. It will be particularly interesting to observe these lines with the same technique as was used in my measurements for iron.

Table VI by no means exhausts the information which may be derived from the data, but it is sufficient to show that these terms behave much like those of iron shown in Table III. There is the same increase of depression with rising level, as well as an indication that the effect for quintet terms is greater than for triplets and singlets. The observations of Gale and Adams, both for iron and for titanium, are thus found to be qualitatively consistent with the data presented in this paper, and their classification of spectral lines evidently has a very definite physical basis in the characteristics of the spectral terms. With the exception of group *c*, as already noted, the distinctions between the pressure groups, though somewhat arbitrary, are useful and convenient. The numerical definition which has now been given to the groups (Table V) permits the extension of the classification to include all identified iron lines, without further observations except as required for distinguishing groups *e* and *d*.

6. DENSITY EFFECT

Havelock[1] and Holtzmark[2] have suggested that pressure effect is in reality a density effect, dependent on coupling between atoms of the same kind, and thus related to the partial pressure rather than to the total pressure. It seems reasonable, on this basis, to expect that the effect would be greatest, not only for a high partial pressure of atoms of the same kind, but also for those atoms of the same kind which are in an identical state of excitation. In other words, the most intense lines of a multiplet should show the greatest displacement; and, since at the temperature of the arc the number of iron atoms in the lower states of excitation far exceeds the number in the higher states, we should expect to find the greatest pressure displacement in those multiplets whose upper terms are at comparatively low energy levels.

Neither of these expectations is fulfilled, but instead the lines of

[1] *Astrophysical Journal*, **35**, 304, 1912.

[2] *Zeitschrift für Physik*, **34**, 722, 1925.

a multiplet behave closely alike and the greatest pressure effect occurs in the case of multiplets having upper terms of highest level. Furthermore, several confirmatory observations may be recalled in this connection, namely: (1) King's[1] measurement of the same displacement under pressure in the furnace for lines produced with large and small vapor density; (2) Humphreys'[2] remark that in his work lines due to impurities in the arc were displaced the same amount as the arc lines themselves; (3) the effect of the nature of the surrounding gas; and (4) the behavior of the enhanced lines observed by Gale and Adams.[3]

The question is sometimes raised as to whether there is any true pressure effect in the strictest sense, whether we may not be measuring something dependent entirely on the width and dissymmetry of the lines instead of an actual displacement to a new position. The foregoing considerations and the new measurements given in this paper may help to dispel such doubts and to establish the existence of a real effect of pressure on the mechanism of the radiating atom. Although no theory at present seems adequate, the new basis now given to the observational side of the problem may assist in developing a satisfactory explanation of the phenomena.

Some of the facts for which a satisfactory theory of the pressure effect must account are: (1) depression of the spectral terms with increase of pressure, the depression being greater for terms of high level than for those of low level, and greater for terms of high multiplicity than for those of low multiplicity at the same level; (2) general increase of width, reversibility, and dissymmetry with increase of pressure, especially above 1 atmosphere; (3) proportionality between change of pressure and displacement of lines over a wide range of pressures; (4) displacement independent of the partial pressure; (5) the fact that lines of Ti^+ show greater displacement than those of Ti; (6) further, that changing the surrounding atmosphere from air or CO_2 to H_2 increases the displacement for Ti^+, but does not change it for Ti.

7. TEMPERATURE EFFECT

Although not germane to the subject of pressure effect, another application of the foregoing method of study is interesting. This

[1] *Loc. cit.* [2] *Loc. cit.* [3] *Loc. cit.*

concerns the temperature effect, for which we select data for iron, titanium, scandium, barium, and calcium from numerous papers by King. In each case the mean energy level has been found for both lower and upper terms for each temperature class, I, II, III, etc., as assigned by King. The data for the rich spectra of iron and titanium were also separated according to wave-length into three divisions, ultra-violet, violet-blue, and green-red. This procedure showed that the classification is somewhat more consistent for the longer wave-lengths, and that with decreasing wave-length the level of upper terms becomes higher, and that of lower terms, lower. This corresponds to the well-known observation that reversibility increases in the ultra-violet and that at a given temperature of the electric furnace there is a fairly definite ultra-violet limit to the spectrum, which may be extended by increase of temperature.

Figure 2 shows the results for iron, the ordinates being expressed in wave-numbers, while the temperature classes are equally spaced as abscissae. It will be noted that class I A has been placed one division lower than class I, and that none of the other classes which are distinguished by the suffix A appear. Lines in such classes frequently were found to belong in multiplets characteristic of the next lower class, and a rule was adopted of assigning all lines in a multiplet to the dominant temperature class. Scandium has nearly the same energy levels for classes III A, III, and IV A. In the case of this element these classes were therefore combined and designated simply by III. For iron it appears that the temperature classification of the ultra-violet lines may be affected somewhat by the mixture of data from absorption and emission spectra; but for the visible region, where only emission spectra were used, the points in Figure 2 lie remarkably close to straight lines having the same slope. From the inclination of these lines to the axes of the diagram, it is found that a progression of one temperature class corresponds to a change in excitation potential of 0.72 volt.

For titanium the points do not lie quite so well on a series of straight lines as in the case of iron; but the same features are well shown, and the slope of the lines indicates a change of 0.69 volt in excitation potential for a change of one temperature class. Scandium and barium, with much less material for study, give, respectively,

0.76 and 0.73 volt, while calcium seems to be quite different, showing a change of only 0.35 volt in excitation potential for a change of one temperature class. Only classes I, II, and III were available for calcium, since the few lines assigned to class IV show no difference of level from that of a large number in class III. Whatever the explanation of the behavior of calcium, it appears that for the other elements examined a progression of one temperature class uniform-

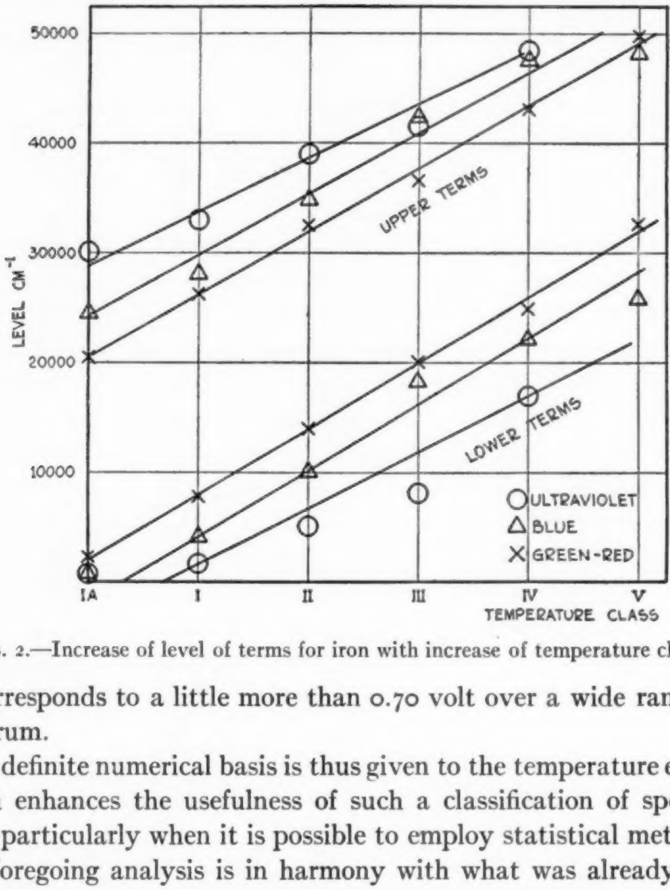

FIG. 2.—Increase of level of terms for iron with increase of temperature class

ly corresponds to a little more than 0.70 volt over a wide range of spectrum.

A definite numerical basis is thus given to the temperature effect, which enhances the usefulness of such a classification of spectral lines, particularly when it is possible to employ statistical methods. The foregoing analysis is in harmony with what was already well established, namely, the real physical connection between the temperature of a gas and the spectrum which it emits.

In conclusion we may recall that Gale and Adams remarked concerning the difficulty of measuring pressure displacements:

. . . . Our experience with titanium at different pressures indicates that the probable error increases almost in proportion to the pressure, so that the use of high pressures brings little gain on account of the deterioration of the lines.

The results communicated in this paper are obviously only a beginning, but they indicate some advantage in studying the phenomena at low pressures. It will be interesting to extend these observations for iron and to include the spectra of other elements as well, particularly that of titanium.

I am indebted to Professor Russell and Miss Charlotte E. Moore for helpful suggestions and for the privilege of using unpublished data on the spectral terms of iron; to Dr. F. M. Walters for generously supplying unpublished material of the same kind; to Mrs. Lawrence Thome, formerly a member of the Computing Division, for assistance in measuring the plates of the first series; and to Mr. W. P. Hoge for measurements and reductions in the latter part of the work.

Carnegie Institution of Washington
Mount Wilson Observatory
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ON THE USE OF THE HODOGRAPHIC METHOD OF LAVES FOR DETERMINING ELEMENTS OF SPECTROSCOPIC ORBITS

By ALEXANDER POGO

ABSTRACT

In the recapitulation of the theory of the method of Laves, the *center* of the orbit (intersection of conjugate diameters) is taken as the *origin* of the *hodograph* instead of the principal *focus* (intersection of the line of nodes with the line of apsides).

It is shown that the length, $a \sin i$ (km), of the major semiaxis (*mean distance*) of the inclined orbit is given by the ratio of the numerical value (km/sec.) of the equal but opposite vectors representing the orbital velocity across the minor axis (*mean orbital velocity*) to the *mean instantaneous motion* (radians per second of time) in the orbit.

The *practical application* of the hodographic method is simplified by placing the *center* of the hodographic circle on the *Schwarzschild S-axis* of the velocity-curve. The *longitude* ω *of the periastron* is read off directly, without the use of a table of sines. The *eccentricity* e of the orbit is obtained as the ratio of the distance between the origin and the center of the hodographic circle to its radius K, without making use of the scale of radial velocities. The length of the *major semiaxis* and the value of the *mass function* are obtained by measurement of the horizontal half-chord through the origin of the hodograph, and by simple multiplications, without the use of a table of logarithms.

The hodograph shows that the *periastron point* and the γ-*axis* must be on *opposite* sides of the mean S-axis, as implied by the formula $S = \gamma + Ke \cos \omega$.

The hodographic method of Professor K. Laves[1] assumes that the γ-axis is already determined by equalizing the areas of the curve of radial velocity above and below it, and that the Schwarzschild[2] S-axis is drawn by halving the amplitude $2K$ of the oscillation in radial velocity. By shifting, along this mean S-axis, the reversed transparent diagram for the distance of half a period, the equal distances d of the periastron and apastron points from the S-axis are determined.

The undetermined inclination of the spectroscopic orbit is eliminated by the simplifying assumption, $i = 90°$.

Let us consider the spectroscopic orbit, drawn on an arbitrary scale, and so oriented that the orbital motion is counterclockwise, and the periastron point is to the right (see Fig. 1). The center of the

[1] *Astrophysical Journal*, **26**, 164, 1907; see also *Astronomische Nachrichten*, **178**, 321, 1908.

[2] *Astronomische Nachrichten*, **152**, 65, 1900; or see R. G. Aitken's *The Binary Stars*, pp. 139 and 149. It is not necessary to represent a period and a half of the velocity-curve, if the precept given below is followed.

ellipse is chosen as the origin of the hodograph.[1] If we draw an arbitrary diameter of the ellipse, and the tangents at its extremities, the corresponding orbital velocities are given, on a certain scale, by the segments of the conjugate diameter intercepted by the hodograph. With our orientation of the orbit, the vectors representing

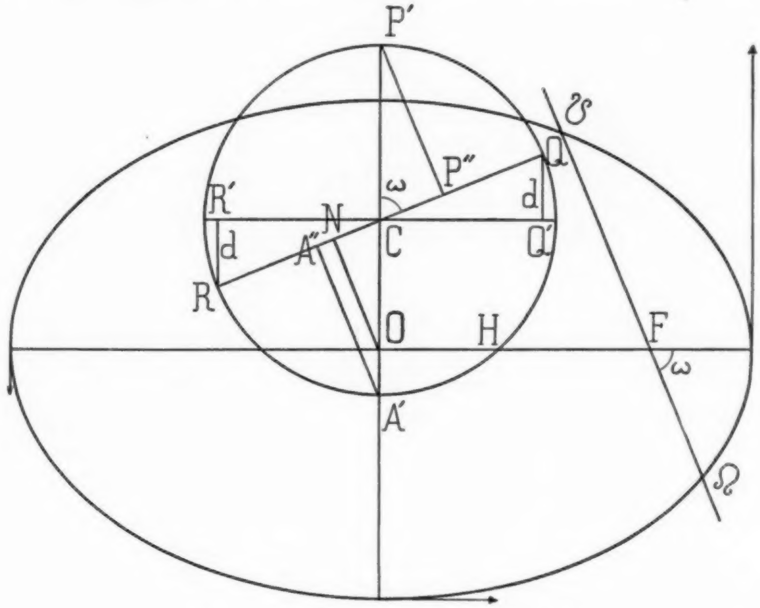


FIG. 1.—Elliptic orbit and its hodograph

the orbital velocities at the periastron and apastron points are the maximum vector OP' and the minimum vector OA', respectively. The origin O of the hodograph divides its vertical diameter in the ratio $\frac{1+e}{1-e}$ of the orbital velocities across the line of apsides, the ratio of the corresponding apsidal radii vectores of the orbit being $\frac{1-e}{1+e}$.

With our orientation of the orbit, the center C of the hodographic circle, of radius K, is always above the origin O of the hodograph,

[1] In *Astrophysical Journal*, **27**, 125, 1908, W. F. King places the center—not the origin—of the hodographic circle in the center of the ellipse, and does not refer to the properties of conjugate diameters. Both Laves and King place the origin of the hodograph in the principal focus of the orbit.

at a distance $OC=Ke$. This distance is projected, on the normal to the line of nodes, in $CN=Ke \cos \omega$, which is equal to the distance between the γ-axis and the S-axis of the curve of radial velocity.

The distance d, from the S-axis, of the periastron or of the apastron point of the velocity-curve, is equal to $K \cos \omega$. The normal to the direction of the line of nodes is therefore the diameter of the hodographic circle giving $2d=A''P''$ for the projection, on the line of sight, of $OP'+A'O=2K$, corresponding to the difference of the vectors OP' and OA' of the orbital velocities across the line of apsides.

The construction, $d=QQ'=RR'$, gives the direction of the normal QR to the line of nodes. The longitude of the periastron is given by the angle QCP', counted in the adopted counterclockwise direction of orbital motion.

The parallel NO to the line of nodes, drawn at a distance $CN=Ke \cos \omega$, gives $OC=Ke$, i. e., the distance of the center of the hodographic circle above its origin. The ratio OC/CP' gives the eccentricity e of the spectroscopic orbit.

Of course, the value of the longitude of the periastron cannot be found precisely by this method, when $d=K \cos \omega$ differs but little from K, i.e., when ω differs but little from 0° or 180°.

The precision of the determination of the eccentricity by this method obviously diminishes when the distance $Ke \cos \omega$ between the S-axis and the γ-axis is very small on account of a very small eccentricity. When the distance $Ke \cos \omega$ between the axes practically disappears because of small values of $\cos \omega$, i.e., when ω differs but little from 90° or 270°, even large values of e cannot be found by this method.

If we now drop the assumption, $i=90°$, that the line of sight is contained in the orbital plane, we can use the hodograph to simplify the computation of the function of mean distance,

$$a \sin i=\frac{86{,}400\, P^{\text{days}}}{2\pi} K\sqrt{1-e^2} \, .$$

The horizontal half-chord OH is the geometric mean of the segments $OP'=K(1+e)$ and $A'O=K(1-e)$ of the vertical diameter, and represents the orbital velocity across the minor axis, i.e., paral-

lel to the line of apsides. If we substitute $OH=\sqrt{K(1+e)\cdot K(1-e)}$ in the expression of the major semiaxis of the inclined orbit, we have

$$a \sin i^{\text{ km}} = 13{,}750 \cdot P^{\text{days}} \cdot OH^{\text{ km/sec}}.$$

To find the value of OH in km/sec., we have to use the scale of radial velocities, which was of no importance in the hodographic determination of ω and e.

For the mechanical interpretation of the foregoing relation between the length of the major semiaxis (*mean* distance, in km) of the inclined orbit and the orbital velocity parallel to the line of apsides (*mean* orbital velocity, in km/sec.), it is useful to recall that $\frac{2\pi}{86{,}400\ P^{\text{days}}}$ is the *mean* instantaneous orbital motion (radians per second of time).

The computation of the mass function, $\frac{m_2^3}{(m_1+m_2)^2}\sin^3 i=$ $[3.0164-10]PK^3(1-e^2)^{\frac{3}{2}}$, is reduced to simple multiplications, if we measure, on the hodograph, the product, $K\sqrt{1-e^2}=OH$. We have

$$\frac{m_2^3}{(m_1+m_2)^2}\sin^3 i = 1.04\cdot 10^{-7}\cdot P^{\text{d}}\cdot \overline{OH}^3\ ,$$

the period being expressed in days, and OH in km/sec.

For the practical application of the foregoing theoretical considerations, we have the following simple precepts (see Fig. 2).

I. DETERMINATION OF γ, K, AND T

Draw the γ-axis bisecting the area of the velocity-curve,[1] and the S-axis bisecting its amplitude $2K$.

Mark, on the S-axis, the length corresponding to a period, then bisect this length. Mark the same three points of the S-axis on a transparent copy of the velocity-curve, reverse it, face downward, and shift it, along the S-axis, until the midperiod-point of the copy coincides, successively, with both end-points marked on the S-axis of

[1] The position of the γ-axis is generally already known from the adjustments of areas necessary for the drawing of a reliable freehand velocity-curve. Its determination requires more time than all the following constructions.

the original drawing. The intersections of the original and the reversed curves give the points P and A, equidistant from the S-axis, the one on the ascending branch of the curve, the other on the descending branch, separated by half a period; P is on the steeper branch; the sharper periastron-arc of the curve intercepts, on the S-axis, less than half a period, the remaining longer segment of the S-axis subtending the flatter apastron-arc; the periastron-arc and the γ-axis are on opposite sides of the mean S-axis.

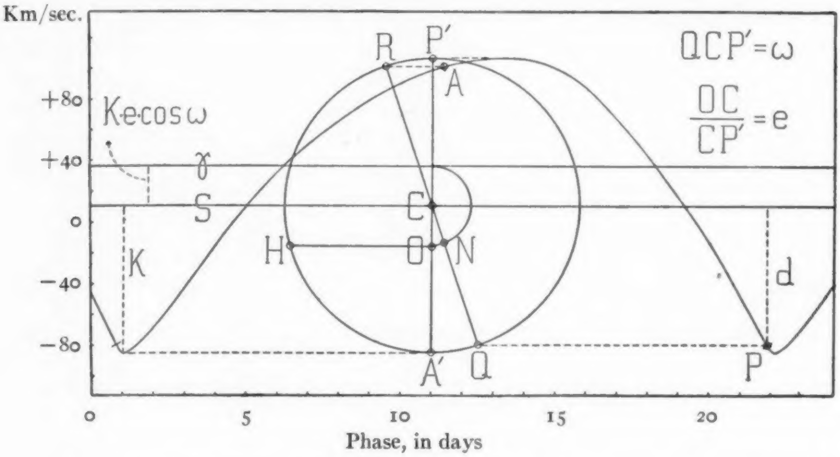


FIG. 2.—Velocity-curve and hodograph of 43 θ^2 Orionis. Phase zero corresponds to J.D. 2,423,741.000 G.M.T.

The abscissa of P determines T, the epoch of periastron passage.

II. HODOGRAPHIC METHOD FOR DETERMINING ω, e, AND $a \sin i$

Construct a circle, with its center at any convenient point on the S-axis, and with the half-amplitude K as its radius.

Find the intersections of the hodograph, at Q and R, with the horizontals through P and A of the velocity-curve. If P is on the descending branch of the velocity-curve, Q is to the right of the vertical diameter $A'P'$; if P is on the ascending branch, Q is to the left of $A'P'$.

Draw the diameter QCR. The angle QCP' is ω, the longitude of

periastron. The angle QCP' is counted counterclockwise, so that $\omega > 180°$, when Q is to the left of $A'P'$.

Lay off, on the radius CQ (or CR, if R is below the S-axis), the length CN equal to the distance between the S-axis and the γ-axis. The normal NO to CN gives O, the origin of the hodograph. The ratio $OC/CP' = Ke/K$ gives e, the eccentricity of the spectroscopic orbit.

Draw the horizontal OH, find its value, in km/sec., on the scale of radial velocities of the diagram. Multiply this value by 13,750 and by the period expressed in days. The product is $a \sin i$, in kilometers.

To find the mass function, multiply $1.04 \cdot 10^{-7}$ by the period expressed in days, and by the cube of OH expressed in km/sec.

Example 1.—Figure 2 reproduces the velocity-curve of $43\theta^2$ Orionis, published by Professor O. Struve.[1] The curve was redrawn on a scale giving a hodographic circle of 109-mm radius. The position of P[2] and of A was found by Schwarzschild's method. The results of the hodographic method are compared in Table I with the published final elements derived from a least-squares solution following a preliminary determination by the method of Lehmann-Filhés.[3]

TABLE I

Element	Hodographic	Lehmann-Filhés
ω	161°	$154^\circ\!.7 \pm 3^\circ\!.2$
e	0.28	0.27 ± 0.02
$a \sin i$	26,600,000 km	27,000,000 km
$f(m)$	$1.711\odot$	$(1.795\odot)$

Example 2.—Figure 3 reproduces the velocity-curves of 66 Eridani, published by Professors E. B. Frost and O. Struve.[4] The original large-scale diagram was used, the radii of the two hodo-

[1] *Astrophysical Journal*, **60**, 159, 1924.

[2] Time of periastron passage, J.D. 2423741.9. To correspond to the epoch given in the table of elements, the position of the point P in the diagram of the original paper should be shifted from the abscissa 3741.0 to 3741.36.

[3] *Astronomische Nachrichten*, **136**, 17, 1894.

[4] *Astrophysical Journal*, **60**, 313, 1924.

graphic circles being 121.5 and 139.0 mm, respectively. A comparison of the results is given in Table II.

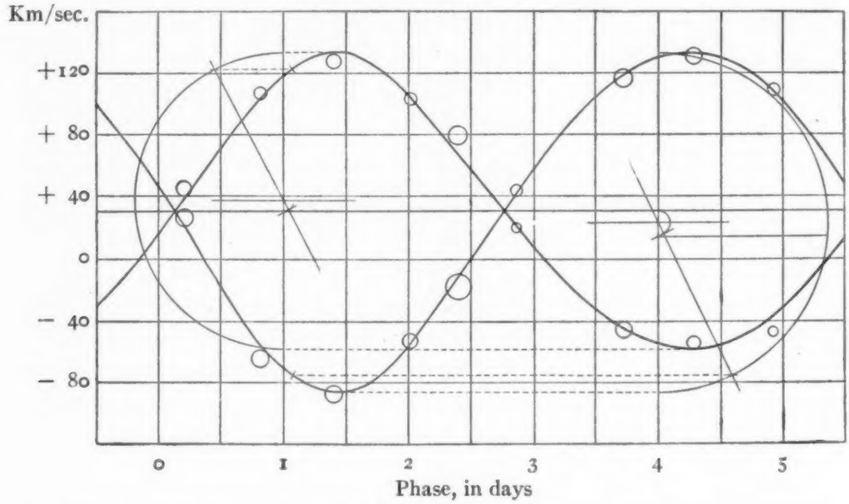


FIG. 3.—Velocity-curves and hodographs of 66 Eridani. Phase zero corresponds to J.D. 2,423,086.500 G.M.T.

TABLE II

Element	Hodographic	Lehmann-Filhés
$\left.\begin{matrix}\omega_1\\ \omega_2+180^\circ\end{matrix}\right\}\omega$	$\left.\begin{matrix}332^\circ\\ 334\end{matrix}\right\}333^\circ$	$335\overset{\circ}{.}9\pm1\overset{\circ}{.}1$
$\left.\begin{matrix}e_1\\ e_2\end{matrix}\right\}e$	$\left.\begin{matrix}0.08\\ 0.08\end{matrix}\right\}0.08$	0.074 ± 0.013
$a_1 \sin i$	7,200,000 km	7,300,000 km
$a_2 \sin i$	8,300,000 km	8,400,000 km
(K_1/K_2)	(0.87)	(0.87)
$m_1 \sin^3 i$	2.6☉	2.5☉
$m_2 \sin^3 i$	2.3☉	2.2☉
(m_2/m_1)	(0.88)	(0.88)

YERKES OBSERVATORY
January 1928

MEASURES OF THE VARIABLE RADIAL VELOCITY OF α CORONAE BOREALIS

By J. HARTMANN

ABSTRACT

Measures are given of forty-two spectrograms of this star, which was found by the author in 1903 to vary in its radial velocity.

A *single plate* of the series *shows* a number of *fine lines* not seen on other plates. *Similar conditions were found* by the author for the star Algol when its spectrum was photographed at *minimum phase*. The *pceuliar plate* of α Coronae was taken at *exactly* the time of *minimum*, as deduced from later photometric measures by Stebbins. The *fine lines* are regarded to be due to *absorption in the atmosphere of the eclipsing companion.*

Herewith are communicated the results of the measurement of forty-two spectrograms of α Coronae Borealis ($\alpha = 15^h 30^m$; $\delta = +27°3'$; mag. 2.3; spectral type, A0) which were made in Potsdam with spectrograph No. 1 during the period July, 1903—May, 1906.

After my discovery in 1903 of the variable radial velocity of this star,[1] I made many further plates of its spectrum in order to determine the elements of its orbit, as well as any possible changes thereof. This work was unfortunately interrupted by my departure from Potsdam, and I am not yet in a position to complete it. Meanwhile, the orbit of the star has been published by F. C. Jordan[2] and by J. B. Cannon.[3]

Therefore, I gladly comply with the request of the editor of this *Journal*, Professor Edwin B. Frost, that my measures should be published here; they may, in fact, have an added value because they extend back for a period of twenty years.

On account of the diffuseness of the spectral lines of this star, all the plates were made with the dispersion of a single prism and generally only three stellar lines, or at most six, could be measured. Hence the results may be uncertain by several kilometers. In Table I, I give the heliocentric values of V, and the Julian Day, counted as formerly from Greenwich Mean Noon. The measurements are

[1] *Astronomische Nachrichten*, **163**, 31, 1903.

[2] *Publications of the Allegheny Observatory*, **1**, 85, 1909.

[3] *Journal of the Royal Astronomical Society of Canada*, **3**, 419, 1909.

my own, but some of the plates were also measured by Mr. Philip Fox, who may publish his results elsewhere. In addition to these forty-two plates, I obtained ten more, extending to the year 1908, but I have not yet been able to measure these.

I should like to call attention here to one matter which seems to me of importance. If the velocities are plotted, Plate I 593 departs very widely from the others, the measured value appearing too negative by 20 km. This particular plate also exhibits another

TABLE I

Plate	J.D.	V	Plate	J.D.	V
I 308	2415898.40	−20.5 km	I 594	2416326.34	− 1.9 km
I 321	2415903.48	+36.4	I 597	2416351.30	− 8.7
I 326	2415904.47	+38.1	I 598	2416352.37	+ 2.9
I 550	2416242.34	−12.1	I 600	2416357.32	+21.3
I 552	2416288.39	+19.7	I 605	2416380.25	−11.2
I 554	2416290.38	+16.7	I 608	2416381.25	−27.6
I 558	2416291.38	+ 0.5	I 613	2416382.24	−25.4
I 567	2416298.38	−20.3	I 618	2416383.24	−37.8
I 571	2416300.35	+ 6.0	I 622	2416385.26	−20.4
I 572	2416300.37	− 2.8	I 623	2416386.26	−17.8
I 575	2416301.33	+23.4	I 624	2416387.24	− 3.3
I 576	2416301.34	+39.4	I 625	2416388.24	+20.4
I 577	2416317.38	− 7.7	I 629	2416389.23	+36.0
I 578	2416317.39	−10.0	I 648	2417016.41	+20.4
I 579	2416318.32	+10.0	I 650	2417017.40	+10.1
I 582	2416319.32	+34.6	I 655	2417024.35	−23.4
I 587	2416320.33	+40.8	I 666	2417027.34	−25.9
I 589	2416321.33	+21.8	I 667	2417029.35	+ 5.2
I 590	2416322.33	+16.3	I 702	2417297.46	+ 4.5
I 592	2416323.32	+12.6	I 718	2417302.39	−25.9
I 593	2416325.31	−16.5	I 719	2417302.40	−25.2

peculiarity in that a large number of fine lines make their appearance in the spectrum (some of them due to iron) which are not visible on the other plates.

In 1904, I discovered the same thing in the spectrum of β Persei; the plates taken during the minimum of light yielded a strongly variant velocity and displayed a quantity of fine lines which could not otherwise be recognized in the spectrum. It was natural to infer that the fine lines were due to absorption in the atmosphere of the companion star and that the alteration in the velocity was at least partially caused by the occultation of one side of the rapidly rotating principal star by the companion. My last task before leaving Pots-

dam was to collect the material for a closer study of this phenomenon, by photographing the spectrum of Algol at every possible minimum. I mentioned this phenomenon of β Persei briefly in a paper in the *Astronomische Nachrichten*, **175**, 364, 1907.

In 1912 Professor Joel Stebbins succeeded in demonstrating that α Coronae Borealis is also a variable of the Algol type.[1] Spectrogram No. I 593 corresponds exactly to the time of minimum light, whence it follows that its peculiarity is to be explained, just as in the case of β Persei, as a result of the eclipse of the principal star by the companion.

La Plata, Argentine Republic
August 17, 1927

[1] *Astrophysical Journal*, **39**, 478, 1914.

REVIEWS

The Structure of the Atom. By E. N. DA C. ANDRADE. New York: Harcourt, Brace & Co., 1927. Pp. 750. Plates 8, Figs. 112. $10.00.

Others who have undertaken to review this very comprehensive book on present views of atomic structure have commented on the inevitable difficulty of any author sitting down to such a task. The present state of flux of men's opinions with respect to the fundamental concepts of the material world, kept violently agitated by a swift succession of new experimental facts, make it almost certain that any attempt at a complete treatise is sure to be, in many ways, out of date before it can be composed and published.

Such books, however, are invaluable to the student because of the great amount of time which they save him. Starting with merely an elementary knowledge of physical laws, he must, of necessity, in one or two years overtake the swiftly advancing frontier of knowledge and keep abreast of it. For the specialist, also, who has difficulty enough in keeping to the forefront in his own particular field, it is equally important that there be available information as to frontier geography in other directions. This is because the boundaries between the different sciences are rapidly becoming vague and, in many places, non-existent. No better example of this can be found than in the present interdependence of physics and astronomy. The latter now chooses to be represented at the social gatherings of the sciences by her daughter, Astrophysics, no longer a débutante and even without a hyphen in her name. The bulk of its material has to do with the interpretation of the radiation which comes to us from the atoms in the stars. Physics, on the other hand, beginning to feel the force of Eddington's remark that 90 per cent of matter in the universe exists at temperatures in excess of a million degrees, sees in the stars important extensions and vast extrapolations of laboratory experience.

From this angle the book under discussion seems unfortunately silent. An astronomer informed on matters celestial will find the book of inestimable value as a summary of terrestrial experience concerning atomic

systems. But the physicist, and especially the spectroscopist, who would know more of the frontiers of cosmic physics, will find nothing except a discussion of the work of Saha on temperature ionization. Even this is taken bodily from the original journals with little critical comment. As a matter of fact, the second sentence of the first paragraph beginning on page 143 is likely to be misleading. It is generally well recognized that the absence of radiation from a given element in no way precludes the presence of that element in a stellar atmosphere.

One is surprised, of course, not to find the name of Laue in an index so replete with material about X-rays. Absence of any but the most casual reference to the spinning electron, and the merest mention of the wave mechanics is, of course, due to the swift march of new ideas subsequent to the production of a latest edition, and cannot be laid at the author's door. The same cannot be said for the failure to include the important field of band spectra. The older editions of Sommerfeld make much of this, and time has justified the attention. Moreover, the book is, in other respects, a follower of Sommerfeld. Of course if the title, *The Structure of the Atom*, is to be taken as explicit, in barring consideration of the molecule, our criticism falls to the ground. In this event we might well look forward to an equally large volume dealing with molecular phenomema.

These are, after all, sins of omission, and no one, aware of the difficulties of making selections in order to prevent exceeding limitations of space, could deal but very lightly with them. Sins of the other type are very rare.

The author's style is simple, unadorned, and beautiful in its clarity. We do not know, even in the writings of the masters in the field, a finer presentation of excitation potentials than that of chapter xii. Chapter xviii, on wave theory and quantum theory, is a splendid piece of critical exposition, and is said to be admirable by one who has himself, perhaps, done the most fundamental work in this domain. The discussion of multiplets in line spectra seems to us far more orderly and clear than that in Sommerfeld's fourth edition. In classes of students not yet proficient in French and German the reviewer insists that this book, if no other, be continually at hand, and can speak, with the greatest enthusiasm, of the well-thumbed condition of their volumes as well as of the few stumbling blocks that the exposition seems to have for the relatively inexperienced reader. We should like to echo Dr. Darrow's query as to why a book, which is sold for $7.30 in England, is offered at $10.00 in this country.

HARVEY B. LEMON

Astronomy. By H. N. Russell, R. S. Dugan, and J. Q. Stewart. Boston: Ginn & Co., 1926. Vol. I, pp. xi+470, Plates 1, Figs. 183, $2.48; Vol. II, pp. xii+461, Plates 1, Figs. 124, $2.48.

This revision of Young's *Manual of Astronomy* is undoubtedly one of the greatest boons that has come to the teachers of astronomy in many a day.

The first volume contains 470 pages. It deals with the general facts concerning the solar system. After a brief introduction, the subjects of "Astronomical Instruments," "Problems of Practical Astronomy," "The Earth as an Astronomical Body," etc., follow. A chapter on "Celestial Mechanics" is also given. The presentation is descriptive, not involving the use of calculus, and follows closely the admirable discussion given by Young in his *General Astronomy* and in his *Manual;* but new material has been added. The chapters which deal with the moon, sun, eclipses, and planets contain the most recent data. The discussion of the physical aspects of the planets is well treated. The answer to the question of "Life on Mars" is given in the light of the recent investigations with spectroscope and thermopile which have been made at various observatories. The volume closes with a chapter on "Comets and Meteors" and a discussion of the "Origin of the Solar System."

The second volume of 461 pages deals with the subject of astrophysics and stellar astronomy. The recent developments in astrophysics are fully discussed. The volume begins with a chapter on "The Analysis of Light." This chapter is followed by one on the "Solar Spectrum," "The Sun's Light and Heat," and a chapter on "Atomic Theory and Astrophysics." These chapters are written in such a manner that the physical principles underlying spectrum analysis are given as well as their applications. There are chapters on "Luminosities, Temperatures and Diameters," "Stars," "Motions of Stars," "Double Stars," "Variable Stars," "Star Clusters and the Milky Way," and "The Nebulae." The last two chapters of the volume have to do with the "Constitution of the Stars" and the "Evolution of the Stars." Each division is written in a brilliant manner, and the knowledge gained by the student is fundamental for understanding the research which is now being done in these fields.

It is stated in the Preface that the preliminary knowledge required of the student for mastering the subject as it is presented in the text is an elementary course in mathematics and in physics. A year's course in Freshman mathematics and a similar course in physics does not seem to be an adequate preparation for most students. As a result the teacher is required to add supplementary lectures or leave out part of the subject matter entirely. If the first plan is followed, the work cannot be done in

a three-hour course extending through the college year. For the purpose of a beginning course in astronomy which is to serve as a general introduction to the subject, it might have been better if one volume had been published instead of two, in which part of the material that is given had been condensed and part omitted. If the text be supplemented with lectures, the work is an admirable one for those who wish to spend more time in astronomy than a three-hour course extending through the year. For this class it would have been better if parts of the second volume had been treated in greater detail.

The second volume lacks a certain pedagogical quality that was characteristic of Young's work, but this is to be expected when one realizes the newness of the material given. We miss the marginal notes that were characteristic of the earlier work. The exercises at the close of many of the chapters are similar to those given in the *Manual*. They are a real help in understanding the material which has been presented. The reference works cited at the end of each chapter should be in the library of every college where the subject of astronomy is taught. The illustrations are good, but they are not so fine as those found in another text which has recently been published. However, the workmanship of the two volumes is in general all that could be desired. The binding and the paper are good and the type excellent. There seems to be very little left to be wished for in the proofreading. The text is remarkably free from errors of all kinds. In these days of exorbitant prices of textbooks, the publishers are to be congratulated upon their good judgment in making the price of this work so reasonable that it may be owned by every student; and it is certain that the book will be often consulted after college days are over.

Our admiration for the work is most sincere. It is brilliantly written, and it is an inspiration to the teacher as well as to the student who studies it. It is the most up-to-date, the best textbook that we have at the present time.

C. C. Crump

Perkins Observatory
Delaware, Ohio

Molecular Spectra in Gases. Bulletin of the National Research Council, Vol. XI, Part 3, No. 57. By Edwin C. Kemble, Raymond T. Birge, Walter F. Colby, F. Wheeler Loomis, and Leigh Page. Washington, D.C.: National Research Council, 1927. Pp. 358. Unbound, $4.00; bound, $4.50.

This *Bulletin* is the first comprehensive survey of the subject of band spectra, a field of investigation which has been much stimulated in re-

cent years by the important successes of the quantum theory. Students of spectroscopy will find it a mine of information, the primary concern having been "to give them an introduction to the subject combining an adequate historical background with as full an account of the present situation as possible." In addition, the authors have included a considerable amount of original work not published elsewhere. Unfortunately, beginners will be somewhat hampered in their search for information on any particular point by the lack of an Index.

The introductory chapter by Kemble gives a general survey of the quantum theory of band spectra. Chapter ii, by Page, is a discussion of quantum dynamics and the correspondence principle with applications to the emission and absorption of radiation by diatomic molecules. Infrared absorption bands, including those due to some of the simpler polyatomic molecules, are treated by Colby in chapter iii. This is the only mention made of bands due to polyatomic molecules. The subject of electronic bands is then taken up by Birge, this chapter constituting more than half of the report. There is an excellent review of the empirical facts about electronic band spectra with their quantum interpretation. The details of the analysis of the various types of bands are here given for the first time, and should be a great aid to new workers in this field of research. Section 7 of this chapter is devoted to a very complete table of molecular constants with references to the original articles. The reviewer has found this valuable table to be indispensable. The newer work which appeared shortly before the author finished his chapter is mentioned in footnotes and in the last section.

In chapter v Loomis discusses the isotopic effect in band spectra in some detail, and in the next chapter he considers the subject of fluorescent band spectra, in particular the resonance spectra of iodine. The final chapter, by Kemble, treats of the forces which govern molecular vibrations, the successes and failures of the Kramers and Pauli treatment of the gyroscopic motion in a rigid molecule, and the diatomic molecular model with an elastically mounted gyroscope. Then comes a discussion of the important contributions of Hund, and a very fine section on the Zeeman effect in band spectra. The last section is devoted to a consideration of the Stark effect and the dielectric constants of di-pole gases.

As usual in the case of a book dealing with a live and growing subject, new important results have appeared since this *Bulletin* went to press. Chief among these are the papers on the application of the new quantum mechanics to molecular spectra, and the successful efforts of R. S. Mulliken and others in correlating the various structure types to be found in band spectra with characteristic electronic transitions.

There are many plates and diagrams, a feature which greatly enhances the usefulness of the report. The cloth binding, hitherto unavailable for bulletins of the National Research Council, is a welcome innovation.

William W. Watson

Müller-Pouillets Lehrbuch der Physik. 11. Auflage. Fünfter Band, Zweite Haelfte: *Physik des Kosmos.* Edited by August Kopff. Braunschweig: Friedrich Vieweg & Sohn Akt. Ges., 1928. Pp xii+595. Figs. 139. Bound, 39.50 RM; paper, 36 RM.

Recent developments in theoretical and practical physics have brought to light the fact that the properties of matter become greatly simplified if its atoms are highly ionized. It is natural, therefore, that physicists are seeking a laboratory that will enable them to study matter under conditions favorable to ionization. These conditions—high temperature and low density in degrees not yet attainable artificially—are met with in the stars, and the last few years have witnessed an increasing amount of interest on the part of physicists for the study of the heavenly bodies.

The appearance of Volume V, Part 2, of Müller-Pouillet's familiar textbook of physics is a notable illustration of this growing connection between pure physics and astronomy. It is, I believe, the first time that an entire volume of a general textbook on physics has been devoted exclusively to modern astrophysics.

The book was planned by O. Lummer and was carried on after his death by the present editor, Professor A. Kopff. As is frequently the case in newer German editions, this volume consists of a number of separate essays contributed by different persons. The treatment of the subject differs somewhat from that usually found. The authors obviously intend to give to the physicist and not so much to the professional astronomer a clear account of the present status of astrophysics. Accordingly, they have avoided technical details, such as names of various objects or their spherical co-ordinates, and have concentrated upon the physical interpretation of astronomical observations.

It is assumed that the reader has no practical knowledge of astronomy, and the book begins with an introductory chapter, contributed by P. ten Bruggencate and H. Kienle, on the fundamental conceptions of astronomy and astrophysics. We find here a condensed account of the systems of co-ordinates and their relation to time, a short explanantion of the methods used for the determination of astronomical distances, a chapter on

"Reduktionsgroessen," on the determination of the intensities of light-sources, color, temperature, and spectral type. Four plates with reproductions of stellar spectra serve to illustrate this article.

Chapter ii, by J. Hopmann, is devoted to astronomical instruments and methods of observation. Amply illustrated by pictures, it gives a clear idea of practically all modern methods of research used by astronomers. A little more space might have been devoted to the subject of measuring the heat from the stars, as this would have been of particular interest to physicists.

P. ten Bruggencate and H. Kienle contribute chapter iii on "The Star as a Radiating Gaseous Sphere." Emden's work on "Gaskugeln" and modern theories of the radiative equilibrium form the essence of this article. The subject is largely of a theoretical nature, and its segregation into a separate chapter is a distinct advantage. A practical application will be found in chapter iv on "The Sun," by R. Emden, and in chapter vi on "The Single Star," by C. Wirtz. The latter especially emphasizes the theoretical explanation of results derived statistically.

Chapter v, by K. Graff, discusses the members of the solar system: the planets, asteroids, satellites, comets, meteors, and the zodiacal light.

The subject of double stars, including spectroscopic binaries, and of variables is treated by J. Hellerich in a concise and interesting manner. Attention is given to the statistical methods, and the author has added a number of tables not previously published in so simple a form.

Chapter viii, written by E. von der Pahlen, is devoted to star-clusters and nebulae. The work of Shapley, of Hubble, and of Bruggencate is given in considerable detail. This brings the reader to chapter ix, on "The Structure of the Stellar System," by A. Kopff. It is an excellent exposition of our present views on this subject, and astronomers will enjoy reading it, not less than physicists.

Chapter x, "Cosmogony," by H. Kienle, summarizes all preceding articles. The ideas of Jeans, Eddington, and Russell are treated in addition to the more classical theories of Laplace, Poincaré, and others.

The book is concluded by a chapter on "Relativity," by A. Kopff.

Consisting, as it does, of contributions by astronomers who are all specialists in their respective branches, the work is remarkably up to date. Practically all new developments (up to 1927) have found a place in one chapter or in another. There is, however, some lack in systematization, due to the participation of so many authors. Thus one looks in vain through chapter viii, "Star-Clusters and Nebulae," for a description of Trumpler's work on open clusters, although his name is mentioned on

page 360. Under "The Stellar System," page 462, we find a more explicit statement, and under "Cosmogony," page 501, there is a reproduction of Trumpler's original diagrams connecting spectrum and luminosity.

It would perhaps be too much to expect a book of this type to be complete in all details. Nevertheless, the volume would have gained if certain features of distinct physical interest had been included. For example, there appears no discussion of the radial velocities of globular clusters. It seems to me that these determinations, made chiefly by Slipher, are so important that no theory can be regarded as complete that does not account for them.

In view of the rapid progress of astrophysics it is not surprising that in a few instances the information given does not quite correspond to the newest results of observations. One such case should be corrected as it is somewhat misleading: The velocities of the center of mass of the system of 12 Lacertae, page 307, have been retracted by R. K. Young,[1] and there is no proof of any connection between the calcium masses and the binary, as is implied by the author.

References to individual papers are given chiefly in footnotes, although some authors have not made as much use of them as others. The printing is clear, and the illustrations are numerous and well chosen. There is an Index at the end of the book, with numerous cross-references.

The book is an important addition to scientific literature. The reviewer is confident that it will be accepted by both physicists and astronomers with as much enthusiasm as the earlier volumes of the Müller-Pouillet.

Otto Struve

Die Bahnbestimmung der Himmelskörper. By Julius Bauschinger. Leipzig: Wilhelm Engelmann, 1928. Zweite Auflage. Pp. xv +671. Figs. 85. Paper, M. 55; bound, M. 59.

In this new edition of the *Bahnbestimmung*, the first edition of which was published in 1906, the author has kept unaltered the original frame of this widely used book. Hardly any textbook covers the field of orbital determination in such an exhaustive way from the point of view of the needs of the practical computer. The geometric treatment of the subject adds greatly to the lucidity of the presentation. This has been characteristic of the lectures of the author, which for a great many years have attracted students to this field.

[1] *Journal of the Royal Astronomical Society of Canada*, **19**, 47, 1925.

The number of pages has increased only from 653 to 671, mainly through the addition of an outline of H. N. Russell's method of determining the elements of an eclipsing binary from photometric data. Other alterations are of a minor nature and consist chiefly in extensions of the list of references. A paragraph (121) has been added about the multiple solutions in the determination of a parabolic orbit, following Oppolzer's discussion of the problem, but we miss more recent contributions to the question, especially Charlier's study[1] from which he concludes that "the determination of a parabolic orbit from three complete observations can only take place in a single way."

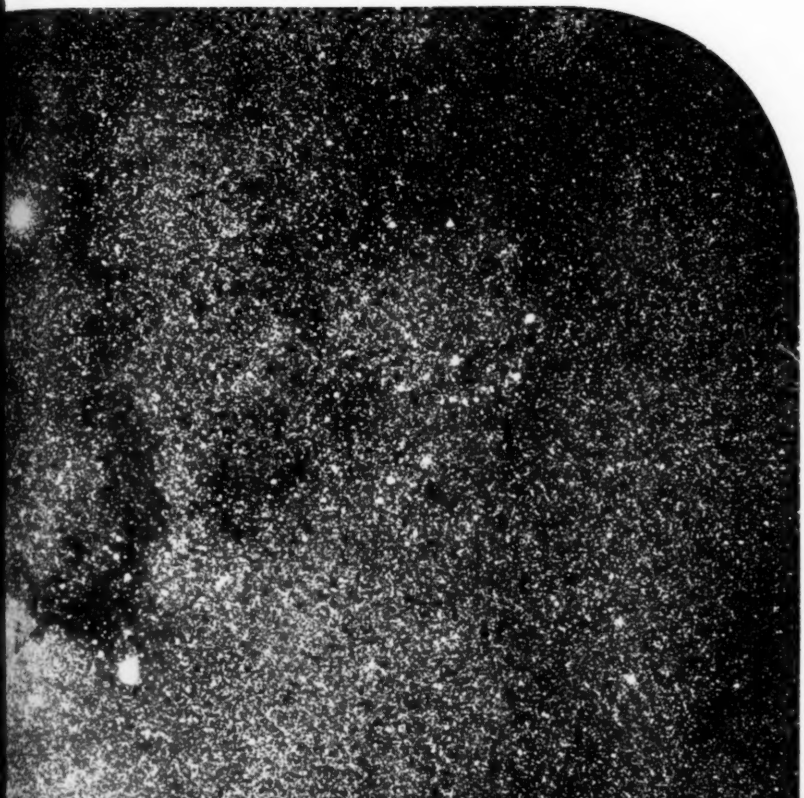
The book is beautifully printed, and its diagrams are excellent. When completed by the new edition of the *Tafeln zur theoretischen Astronomie*, which is in preparation by the same author, the work will constitute a first-class source of reference for any astronomical library.

G. Van Biesbroeck

[1] *Monthly Notices*, **71**, 457, 1911.

MILKY W MONOCEROS

$\alpha = 6^h 36^m$, $\delta = +$ Scale: 1°



NOCEROS

Scale: $1° = 0.93$ cm